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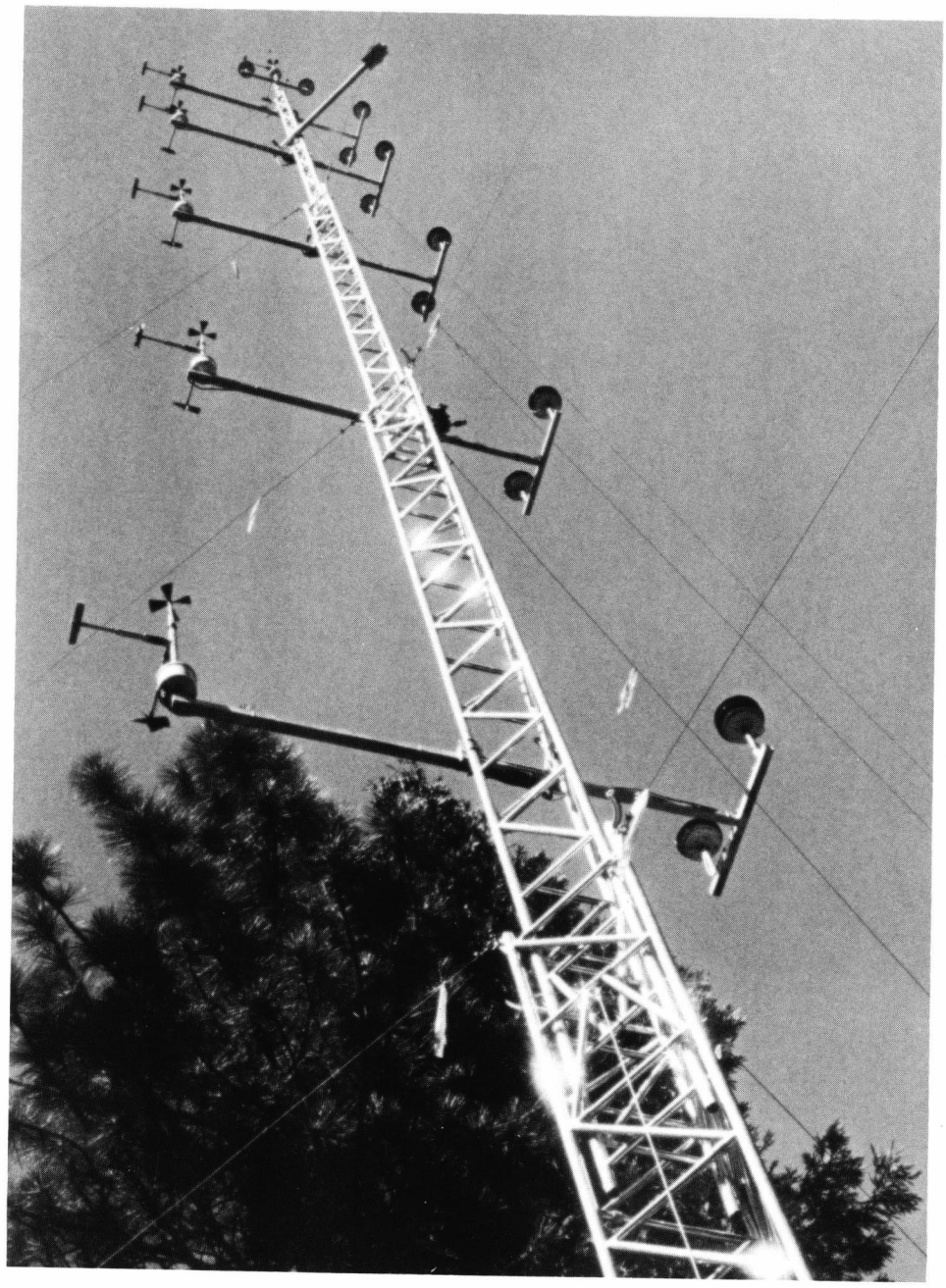
COMPARISON OF FSCBG2 AND FSCBG3 AERIAL SPRAY MODEL PREDICTIONS WITH FIELD MEASUREMENTS



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MARCH 1990

COMPARISON OF FSCBG2 AND FSCBG3 AERIAL SPRAY MODEL PREDICTIONS WITH FIELD MEASUREMENTS

A Program WIND Report

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The FSCBG aerial spray model was developed under the joint sponsorship of U.S. Army Dugway Proving Ground (DPG) and the U.S. Department of Agriculture Forest Service (FS). The FSCBG model is designed to predict concentration, dosage, and deposition patterns of spray material downwind from aerial releases. In making these calculations, the model is capable of considering the effects of aircraft wake vortices on initial drop trajectories, drop evaporation, atmospheric dispersion, and drop penetration of forest canopies. The model was recently extended from a research tool to operational models for use on mainframe (FSCBG2) and personal (FSCBG3) computers. As an option the FSCBG2 and FSCBG3 models also incorporate the AGDISP model, which provides a much more vigorous mathematical description of aircraft wake effects on drop trajectories than the simple wake effects algorithm of the original FSCBG model.
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FOREWORD

Program WIND (Winds In Nonuniform Domains) is a joint meteorological research effort by the U.S. Department of Agriculture, Forest Service, and the U.S. Army Dugway Proving Ground and Atmospheric Sciences Laboratory. Field studies were conducted in northern California during 1985 and 1987 to collect data for meteorological model development and evaluation. As part of Program WIND, cooperation between the Forest Service and Dugway Proving Ground resulted in the advancement of the FSCBG (Forest Service, Cramer, Barry, and Grim) aerial spray model from a research tool to operational models for use on main frame (FSCBG2) and personal (FSCBG3) computers. The work described in this report was sponsored by the Forest Service as part of the Program WIND cooperative effort. The authors wish to acknowledge the support and helpful suggestions provided by Mr. John W. Barry, the Forest Service Program Manager for Program WIND. This report was typed by Mrs. Susan Gross, Meteorology Division, Materiel Test Directorate, Dugway Proving Ground. Assistance in the preparation of the technical illustrations was provided by Mr. John White and Mr. Robert Feldman, both of the Meteorology Division. The authors also thank Dr. Steven R. Hanna of Sigma Research Corporation for providing the statistical analysis software used in this study and Dr. Milt Teske of Continuum Dynamics Inc. for his guidance in the selection of inputs to the AGDISP wake turbulence model.

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SECTION 1. INTRODUCTION

The U.S. Department of Agriculture, Forest Service (FS) and U.S. Army have similar interests in understanding the behavior of aerial spray releases from the time the spray is released from the aircraft until it is deposited or dispersed to airborne concentrations that are environmentally insignificant. For example, the FS uses aerial spray applications as one of several methods to manage forest pests such as the western spruce budworm and tussock moth. Because mathematical spray dispersion models are useful in determining the interactions of the many factors affecting spray operations, the FS and U.S. Army have supported the development and application of these models over many years (Cramer et al., 1972; Barry and Ekblad, 1983; and others). Major computerized models resulting from these efforts include the FSCBG (Forest Service, Cramer, Barry, and Grim) model for predicting spray dispersion above and deposition within forest canopies (Dumbauld et al., 1980) and the AGDISP (Agricultural Dispersal) model for predicting drop trajectories in aircraft wakes (Teske, 1986). Bjorklund et al. (1988) combined the FSCBG and AGDISP models into a single, integrated FSCBG Version 2 (FSCBG2) for use on main-frame computers. The FSCBG2 model allows the use of the AGDISP algorithms to predict spray behavior as long as this behavior is dominated by aircraft wake effects and the FSCBG dispersion algorithms to predict spray behavior after atmospheric diffusion processes become dominant. More recently, the FS (Curbishley and Skyler, 1989) modified the FSCBG2 code to develop a personal computer FSCBG Version 3 [FSCBG(PC) or FSCBG3]. The technical basis of the FSCBG2 and FSCBG3 models is discussed in Appendix A.

This report describes a comparison of FSCBG2/FSCBG3 model predictions with measurements made during two field programs. The first series of spray trials (Boyle et al., 1975) was conducted at Dugway Proving Ground, Utah using a DC-7B aircraft specially equipped for large-scale applications of insecticides. The second trial series (Rafferty et al., 1988) was conducted near Red Bluff, California in conjunction with Phase III of Program WIND (Winds In Nonuniform Domains), a cooperative field meteorological study by the U.S. Army and FS. During the Phase III spray experiment, a C-130 aircraft and a Bell 205 helicopter made spray releases above a forest near the interface between the forest and an open area. We used the statistical analysis software described by Hanna (1989) to quantify the performance of the FSCBG2 and FSCBG3 models for the two data sets. Of particular interest in this evaluation was the degree to which the AGDISP algorithms used by the models' "complex" aircraft wake effects option improve the correspondence between predictions and measurements over that obtained using the "simple" wake effects option of the original FSCBG model. Also, because FSCBG2 and FSCBG3 differ slightly in the point at which drops are transferred from the AGDISP algorithms to the FSCBG dispersion algorithms (see Appendix A), the difference in performance of the two complex wake options was of interest. Consequently, the model evaluation considered models henceforth identified as:

Model 1: FSCBG2/FSCBG3 with no wake effects

Model 2: FSCBG2/FSCBG3 with simple wake effects

Model 3: FSCBG2 with complex wake effects

Model 4: FSCBG3 with complex wake effects.

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SECTION 2. DESCRIPTION OF THE FIELD TRIALS

2.1 UN SPRAY TRIALS

Spray trials sponsored by the Food and Agriculture Organization of the United Nations (UN) were conducted at Dugway Proving Ground in October 1974 to investigate the feasibility of using four-engined aircraft to disseminate insecticides, agricultural chemicals, or seeds over broad areas (see Boyle et al., 1975 and Dumbauld et al., 1976). The Douglas DC-7B aircraft used in these trials was configured with a full-span spray boom mounted above the trailing edge of each wing. Two types of spray materials were used in the DC-7B trials. Duphar™, a low-volatility solvent, was used in Trials 1-6 and 1-7 and No. 2 Fuel Oil was used in the seven other trials. Du Pont oil red dye was added to both materials to facilitate the deposition measurements which were made using 17- by 20-cm Printflex™ cards placed directly on the ground. Spray drops deposited on the Printflex™ cards produced red stains that were counted and sized by microscopic analysis. The drop stain sizes on the cards were converted to the appropriate airborne drop size using an experimentally determined relationship. The drop count information was then used to compute the drop-size distribution and mass deposition. The composite mass median drop diameters for the Duphar™ and fuel oil trials were 66 and 55 μm, respectively. Less than 1 percent of the total mass of each spray material was contained in drops with diameters above 150 μm. Because of the relatively small drops, the behavior of the spray is likely to have been significantly affected by the aircraft's wake vortices and atmospheric turbulence. The dates and times of the UN spray trials are listed in Table 1.

Two different sampling grids were used in the UN spray trials. Figure 1 shows the sampling grid for the crosswind trials in which the aircraft's flight path was approximately perpendicular to the mean wind direction. The open circles in the figure indicate the positions of the Printflex™ cards. Sampling Lines A, B, and C extended about 1.5 km downwind from the flight path and Line B continued beyond this point to about 16 km from the flight path. Cylindrical (pipecleaner) samplers were placed on Tower 00 at 2-m intervals between 2 and 92 m, and dye leached from these samplers was used to estimate the dissemination efficiency of the aircraft's spray system. Wind and temperature measurements were also made at multiple levels between 2 and 96 m on Tower 00.

Figure 2 shows the sampling grid for the two inwind UN spray trials in which the aircraft's flight path was almost directly into the wind. The card deposition samplers were placed at 46-m intervals on sampling Lines D, E, and F, which were separated by 1097 m. As shown by Figure 2, the flight paths for both of the inwind trials crossed Lines D, E, and F near their centers. Wind and temperature measurements were made at 2, 16, and 32 m on Tower 12. No attempt was made to determine the spray system's dissemination efficiency during the inwind trials.

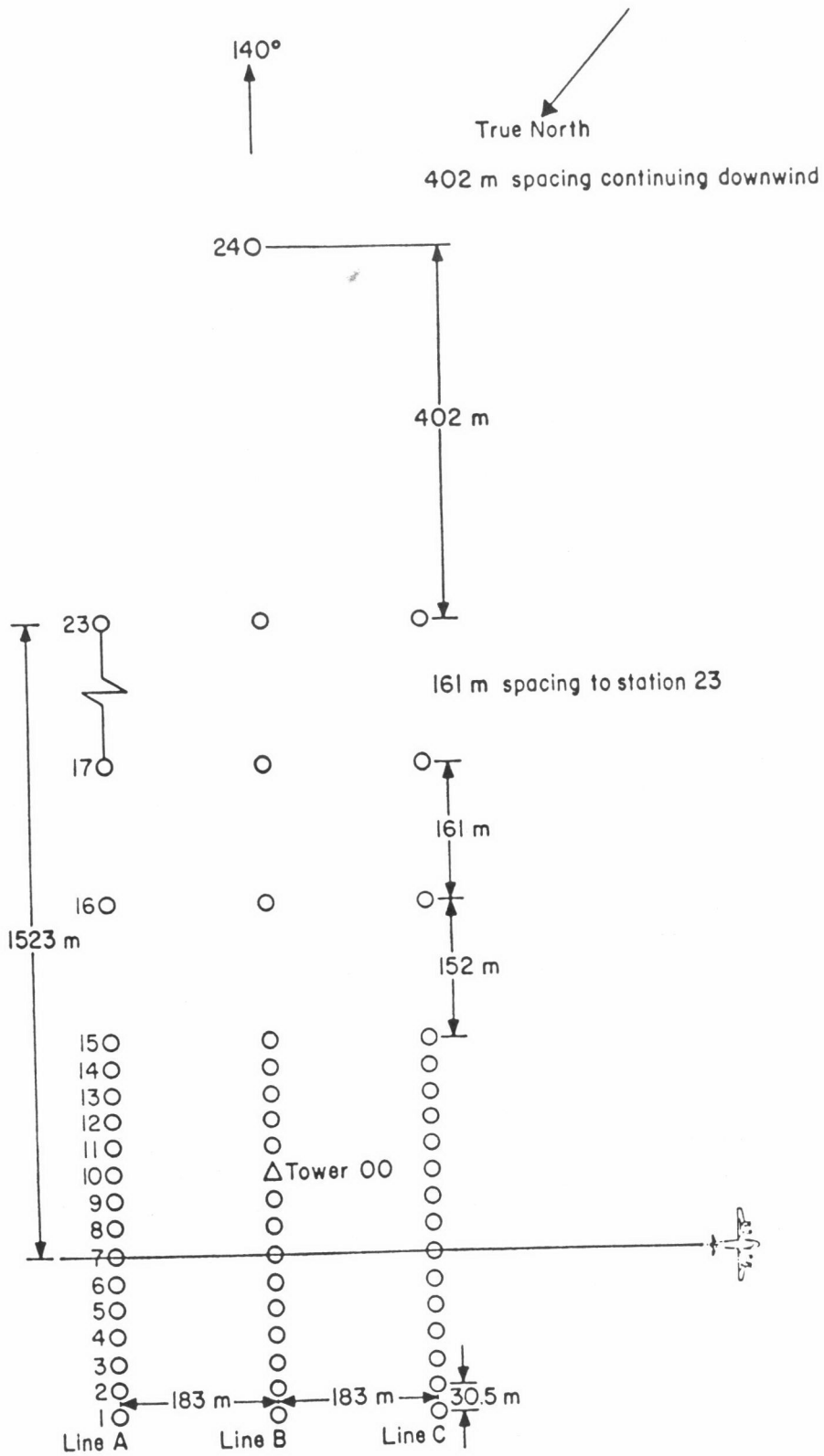

Figure 1. Sampling Grid for the Crosswind DC-7B Spray Trials.

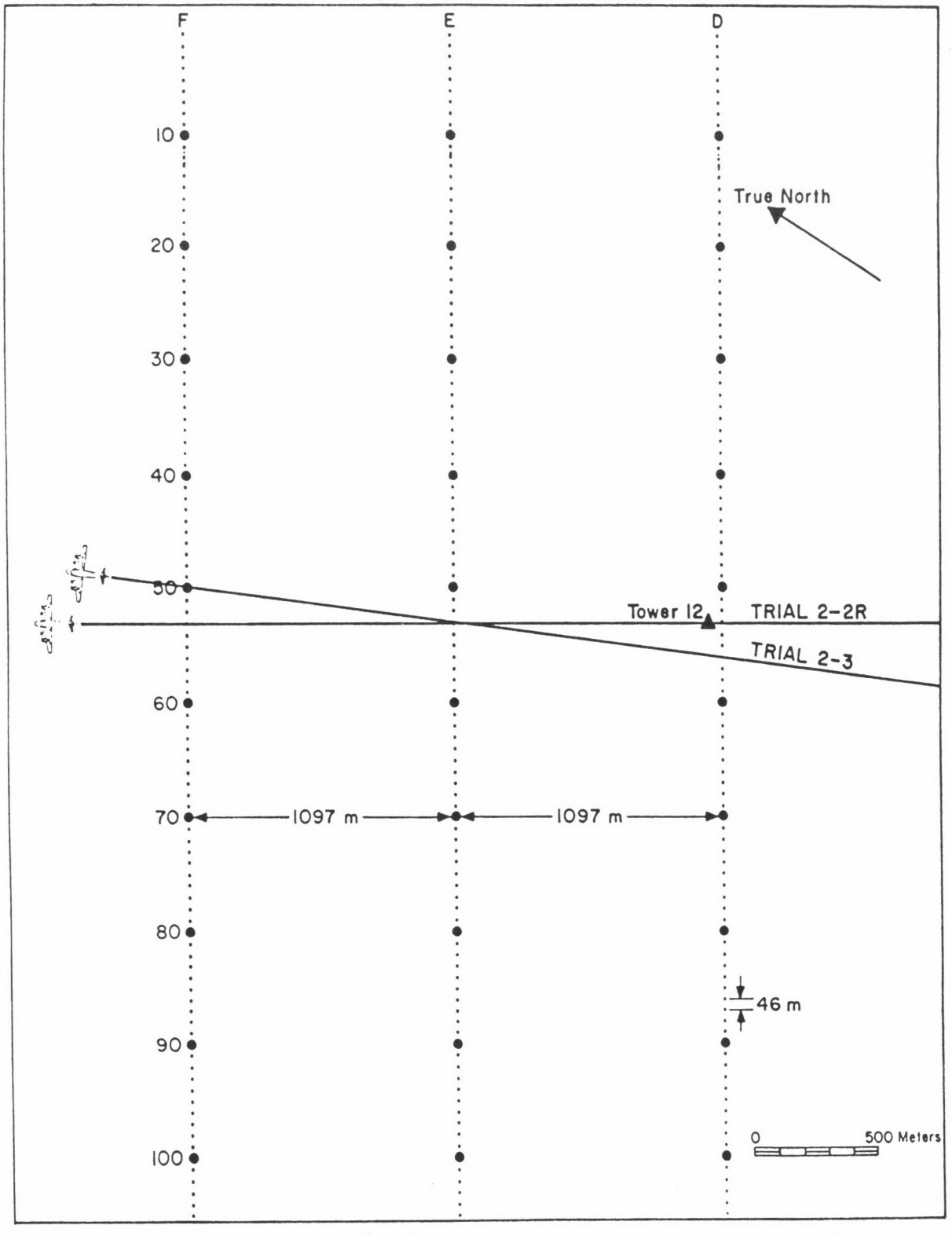

Figure 2. Sampling Grid for the Inwind DC-7B Spray Trials.

Table 1. Dates and Times of the UN and Program WIND Spray Trials.

Trial	Date	Spray Time (LST)[a]	Sunrise (LST)	Spray Line Orientation
		UN Spray Trials		
1-5	17 Oct 74	1249	0644	Crosswind
1-6	17 Oct 74	0953	0644	Crosswind
1-7	16 Oct 74	1434	0643	Crosswind
2-2R	10 Oct 74	1048	0637	Inwind
2-3	10 Oct 74	1247	0637	Inwind
		Program WIND Spray Trials		
A-1	23 Apr 86	0653	0517	Inwind
A-2	24 Apr 86	0621	0516	Crosswind
A-3	25 Apr 86	0743	0515	Inwind
A-4	26 Apr 86	0612	0513	Crosswind
A-5	27 Apr 86	0610	0512	Inwind
A-6	28 Apr 86	0553	0510	Crosswind
B-1	01 May 86	0601	0507	Inwind
B-2	02 May 86	0552	0505	Inwind
B-3	06 May 86	0551	0500	Crosswind
B-4	07 May 86	0557	0458	Inwind

[a]MST for the UN spray trials and PST for the Program WIND spray trials.

2.2 PROGRAM WIND FOREST SPRAY TRIALS

During the spring of 1986, an aerial spray dispersion experiment was conducted in conjunction with Program WIND Phase III (see Rafferty et al., 1988 and 1989). The experiment, which was designed to provide field data for the evaluation of the FSCBG2 model, was conducted in a mixed conifer forest about 30 km east-northeast of Red Bluff, California. This site was chosen because the early morning drainage winds expected along this western slope of the Sierra Nevada Mountains would carry sprayed material from the wooded area into the open. Six trials were conducted with a four-engined C-130 transport used by the U.S. Air Force in pest control and four trials were conducted with a Bell 205 helicopter typical of the rotary-wing aircraft used by the FS in pest control. The dates and times of these trials are listed in Table 1. Both aircraft sprayed a mixture of water, glycerine, Du Pont oil red dye, and manganese sulfate. The dye was added to provide machine-readable stains on Kromekote™ sampling cards, which were analyzed in the same manner as the Printflex™ cards used in the UN Spray Trials. The mass median drop diameters for the C-130 and helicopter trials were 175 and 344 μm, respectively. Mylar™ sheets were used to provide a second estimate of mass deposition. These sheets were washed in a chemical solution which was then analyzed for manganese from the manganese sulfate additive. The minimum detection level for the mylar sheets was 23.5 mg m^{-2} for trial A-1 and 4.7 mg m^{-2} for all other trials. The glycerine was added to the spray mixture to suppress evaporation. Based on the Mylar sampler data, mass recovery estimates for the sampling grid were 71 and 59 percent for the

C-130 and helicopter trials, respectively. Under the assumption of no evaporation, the FSCBG2 model estimates of below canopy deposition were 71 and 69 percent for the C-130 and helicopter trials, respectively (Rafferty et al., 1988). These results indicate that the glycerine was very effective in suppressing evaporation.

Figure 3 shows the sampling grid for the forest spray dispersion study. The spray releases were made along a north-south line (perpendicular to the slope and parallel to the interface between the forest and open area). During each of the C-130 trials, two aircraft passes were made at distances of 175 to 350 m from the forest edge and heights of 46 to 76 m. The helicopter trials consisted of six to ten passes at distances of 85 to 450 m from the forest edge and a height of 46 m. The Kromekote™ and Mylar™ deposition samplers were placed on the ground at the locations shown by the open circles. Table 2 lists the downgrid distance and the number and spacing of the sampling positions along sampling rows parallel to the spray lines. U.S. Army Atmospheric Sciences Laboratory operated three 32-m meteorological towers during the spray trials. Tower 1 was located in the open about 480 m west of the forest interface, Tower 2 (indicated by the triangle in Figure 3) was located in the forest about 110 m east of the interface, and Tower 3 was located in the forest about 550 m east of the interface. Wind and temperature measurements were made at eight levels between 2.4 and 30 m on these towers.

Table 2. Program WIND Phase III Sampler Downgrid Distances, Spacings, and Numbers.

Downgrid Distance (m)	Crossgrid Sampler Spacing (m)	Number of Samplers
-550	--	1
-350	--	1
-150	--	1
0	50	5
150	50	5
200	25	9
250	25	5
300	25	9
350	50	17
500	50	5
550	--	1
650	50	5
750	--	1
850	--	1
950	--	1
1150	--	1
1350	--	1
1850	--	1
2350	--	1

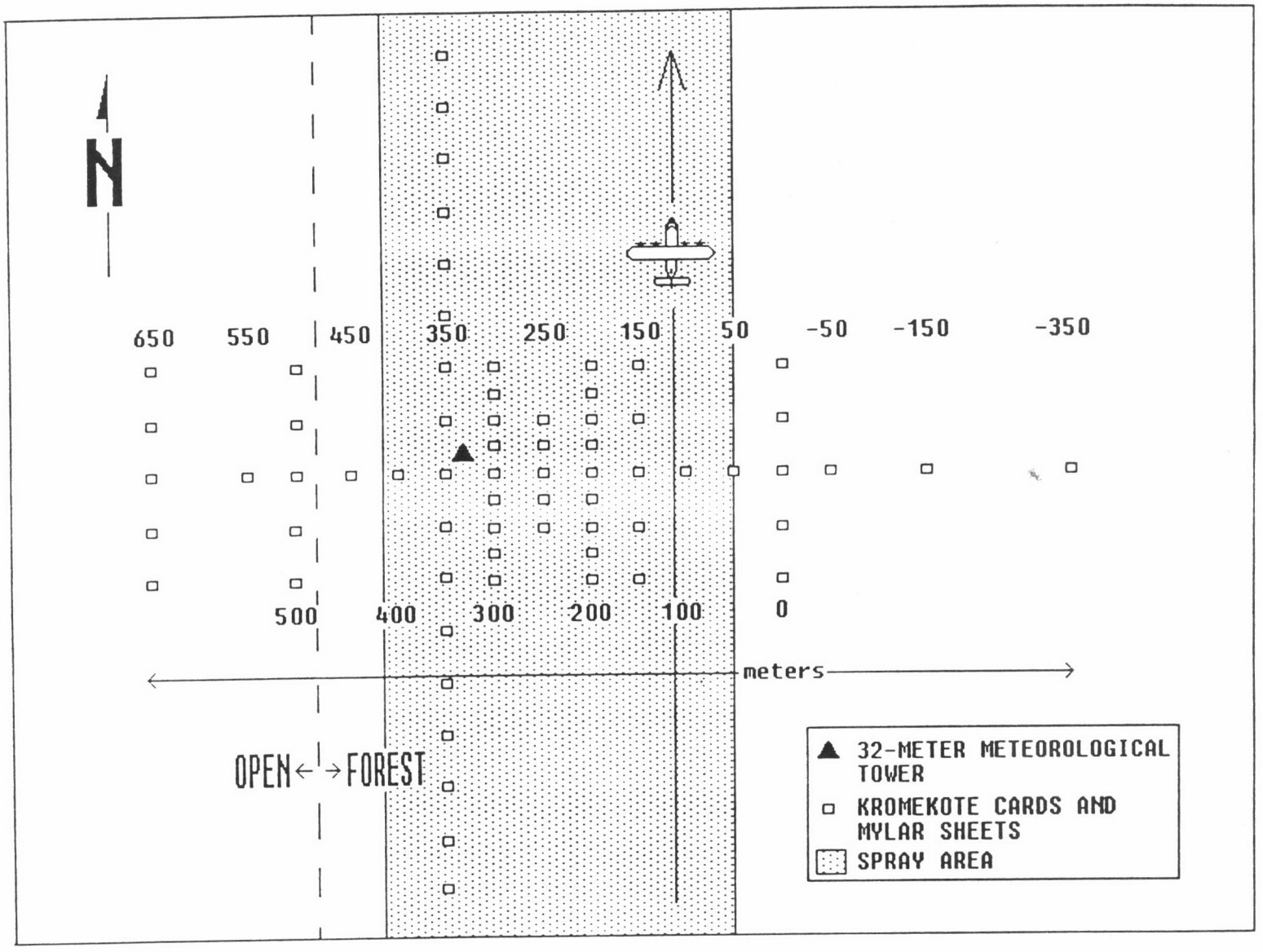

Figure 3. Sampling Grid for the Program WIND Spray Dispersion Experiment.

SECTION 3. MODEL PREDICTIONS

3.1 DATA ANALYSIS PROCEDURES

The FSCBG2 AND FSCBG3 model deposition calculations were made for grid points that exactly corresponded to the deposition sampler locations for the two aerial spray test series described in Section 2. To simplify the comparison of model predictions and measurements, both the predicted and measured deposition values were averaged crossgrid to obtain a single set of predicted and measured deposition values at each downgrid distance. (In theory, there should be no crossgrid variation in deposition for crosswind releases because the crossgrid sampling rows were parallel to and much shorter than the dissemination lines.) If a deposition measurement was not available for a sampling location, that location was also excluded in determining the average predicted deposition for the downgrid distance. If measured deposition was below the measurement threshold, it was averaged as zero. The crosswind trials of the UN spray trials had three crossgrid sampling locations at downgrid distances to 1.5 km (see Figure 1), while the inwind trials had three sampling lines intersecting the dissemination lines (see Figure 2). The same sampling grid was used for both the crosswind and inwind Program WIND forest spray trials. As indicated by Figure 3 and Table 2, data from as many as 17 sampler locations were used to compute crossgrid average deposition. However, only one point on the grid centerline was available to estimate deposition at downgrid distances beyond 650 km.

The FSCBG models do not have provision for modeling a discontinuous forest such as the one that existed at the Program WIND site. Because the models assume that the forest is continuous and uniform at all downwind distances, the calculation of deposition in the open area beyond the forest (downgrid distances of 500 m and greater) presents a problem. If the canopy mode is used, the predicted deposition should be too low because of the assumed existence of trees beyond the actual forest edge. However, if the calculations are made with no forest, the predicted deposition should be too high because the drops will not be subjected to interception and removal by the canopy on their way to the open area. Because of this problem, we calculated deposition both with and without the forest canopy for the Program WIND trials. We used the with-canopy model results at all distances for the inwind trials and at distances through 550 m downgrid for the crosswind trials. We used the without-canopy model results at distances of 650 m and greater for the crosswind trials.

3.2 MODEL INPUTS

3.2.1 Aircraft and Source Inputs

Table 3 lists the C-130, Bell 205 helicopter, and DC-7B aircraft parameters required by the simple and complex wake effects algorithms of the FSCBG2 and FSCBG3 models. The C-130 and helicopter parameters are internal defaults from the models' data bases except for the propeller speed of the C-130, which was provided by the Air Force spray team. The DC-7B parameters were derived from information in the Boyle et al. (1975) report and information provided by Teske (private communication, 1989). If no wake effects are considered in the model calculations, the user must specify an initial source radius. In each case, this radius was defined as one-half the wing or rotor span.

Table 3. Aircraft Physical Parameters.

Parameter	C-130	Bell 205	DC-7B
Weight (kg)	51,000	1423	37,322
Wingspan (m)	40.41	10.16	35.80
Propeller RPM	2200	400	2900
Propeller Radius (m)	2.06	--	2.06
Propeller Efficiency	0.8	--	0.8
Engine Centerline Offset (m)	±10.1, ±5.1	--	±8.0, ±3.6
Vert. Displacement of Engines (m)	-0.9	--	0
Planform Area (m^2)	157.19	--	142.0
Drag Coefficient	0.1	--	0.1

The background turbulence, background turbulent macroscale, and vortex decay coefficient used in the FSCBG2 and FSCBG3 model calculations with complex wake effects were based on the recommendations of Teske (private communication, 1989), one of the developers of the AGDISP model. These values differ from the inputs in previous model calculations for the Program WIND spray trials (Rafferty et al., 1988 and 1989). The background turbulence q^2 was computed from the relationship

$$q^2 = 2(\sigma_A'^2 + \sigma_E'^2)u^2 \qquad (1)$$

where u is the mean wind speed and σ_A' and σ_E' are the standard deviations in radians of the wind azimuth and elevation angles, respectively. Because Teske recommended that the background turbulent macroscale be a height above the release height, it was set to 100 m for all trials. The vortex decay coefficient A was defined by the empirical relationship

$$A = 0.56/q \qquad (2)$$

where q is in meters per second. Table 4 lists the values of q^2 and A used in the model calculations. The σ_A' and σ_E' values used to compute these parameters are given in the next subsection.

During the UN spray trials, two spray nozzle configurations employing 40 or 48 total nozzles were used. Because of the time consumed by the complex wake effects algorithms in calculating the fate of drops disseminated in each

Table 4. Background Turbulence and Vortex Decay Coefficients.

Trial	Background Turbulence ($m^2 s^{-2}$)	Vortex Decay Coefficient
	UN Spray Trials	
1-5	1.5198	0.454
1-6	0.1945	1.270
1-7	0.5358	0.765
2-2R	2.3028	0.369
2-3	3.4741	0.300
	Program WIND Spray Trials	
A-1	0.0563	2.360
A-2	0.5650	0.745
A-3	0.3440	0.955
A-4	0.4710	0.816
A-5	0.2260	1.180
A-6	0.0837	1.940
B-1	1.1500	0.523
B-2	6.7600	0.215
B-3	0.2260	1.180
B-4	0.0951	1.820

drop-size category from each nozzle, the number of nozzles for each of the two configurations was reduced in the model calculations by grouping nozzles in the same location. This procedure resulted in 10 and 6 model nozzles instead of the 40 and 48 actual nozzles. A similar reduction in nozzles was performed for the Program WIND trials in which the 50 nozzles on the C-130 and the 34 nozzles on the Bell 205 helicopter were both reduced to 10. The positions of the nozzles with respect to the aircraft centerline are listed in Table 5 for each trial.

Table 6 lists the aircraft speeds and dissemination heights, while Table 7 gives the spray line lengths, locations, and dissemination rates. The dissemination rates for the UN spray trials were adjusted using the dissemination efficiencies reported by Boyle et al. (1975). The dissemination efficiency, which accounts for evaporation, was determined by Boyle et al. (1975) for each crosswind UN spray trial from the mass recovery on an array of vertical samplers on Tower 00 (see Figure 1). Dissemination efficiencies for the inwind trials were assumed to be the same as for the crosswind trials with the same spray material. The good agreement between the measured spray recovery for the Program WIND spray trials and the recovery predicted assuming no evaporation (Rafferty et al., 1988) indicates that the glycerin effectively suppressed evaporation. Consequently, the dissemination efficiency was assumed to be 100 percent for these trials.

The drop-size distributions for the UN and Program WIND spray trials were obtained by sizing and counting the drop stains on the sampling cards. As noted in Section 2, the stain sizes were empirically related to the drop sizes. Table 8 lists the drop-size distributions measured during the UN spray trials. Prior to the Program WIND spray trials, characterization trials were conducted by flying the two spray aircraft over lines of sampling cards in the open. These drop-size distributions are summarized in Table 9.

3.2.2 Forest Inputs

The model calculations for the Program WIND spray trials included the use of the analytic canopy penetration algorithm, which allows the user to enter up to three tree types within the simulated forest. Each tree is assumed to have a uniform stand density, height, shape, and foliage density. During Program WIND, a forest characterization study (Klein and Boom, 1987) was performed at the spray deposition site by FS personnel. Using their data, a three-storied forest of ponderosa pine (50 stems per acre), incense cedar (14 stems per acre), and woody ground cover (65 stems per acre) with mean heights of 24, 8.3, and 4.8 m, respectively, was used in the canopy penetration model. The probability of penetration was set at 0.62 for the ponderosa pine and 0.38 for the more dense incense cedar and ground cover. Table 10 lists the widths of the tree profiles for each of the three tree types used in the model predictions. As is typical of many western forests, the uniformity of the tree cover is quite variable with open areas occurring through the stand.

Table 5. Aircraft Spray Nozzle Locations.

Trials	Number of Actual Nozzles	Model Nozzle Locations (m from aircraft centerline)
	UN Spray Trials	
1-5, 1-6, 2-2R	40	±6.16, ±14.54, ±15.55, ±16.44, ±17.29
1-7, 2-3	48	±3.78, ±8.64, ±16.87
	Program WIND Spray Trials	
all A	50	±10.96, ±12.67, ±14.29 ±16.11, ±17.82
all B	34	±1.47, ±2.15, ±2.99 ±3.79, ±4.52

Table 6. Aircraft Speeds and Dissemination Heights.

Trial Number	Aircraft Speed ($m\ s^{-1}$)	Dissemination Height (m)
	UN Spray Trials	
1-5	111.2	52.0
1-6	111.2	46.0
1-7	111.2	40.0
2-2R	111.2	45.7
2-3	111.2	27.4
	Program WIND Spray Trials	
A-1	103.0	76.2
A-2	103.0	76.2
A-3	103.0	45.7
A-4	103.0	76.2
A-5	106.0	61.0
A-6	103.8	61.0
B-1	25.5	45.7
B-2	24.6	45.7
B-3	22.4	45.7
B-4	22.4	45.7

Table 7. Dissemination Line Information.

Trial	Spray Line	Length (m)	Downgrid Distance (m)	Source Strength ($mg\ m^{-1}$)
		UN Spray Trails		
1-5	1	14,080	0	14.38
1-6	1	7,376	0	27.32
1-7	1	7,488	0	12.28
2-2R	1	10,280	0	14.38
2-3	1	8,662	0	5.99
		Program WIND Spray Trials		
A1	1	1,544	150	79.9
	2	1,647	250	79.9
A2	1	1,544	150	82.5
	2	1,544	265	82.5
A3	1	1,544	250	99.1
	2	1,441	325	99.1
A4	1	1,235	225	99.0
	2	1,133	150	99.0
A5	1	1,441	150	99.8
	2	1,441	255	99.8
A6	1	1,463	200	98.3
	2	1,442	100	99.8
B1	1	968	200	51.3
	2	994	170	51.3
	3	994	140	51.3
	4	815	110	51.3
	5	892	80	51.3
	6	943	50	51.3

Table 7. Dissemination Line Information (Cont'd).

Trial	Spray Line	Length (m)	Downgrid Distance (m)	Source Strength ($m\ s\ m^{-1}$)
B2	1	983	275	34.0
	2	1,008	225	34.0
	3	1,008	325	34.0
	4	934	195	34.0
	5	934	355	34.0
	6	836	165	34.0
	7	934	385	34.0
	8	1,057	135	34.0
	9	1,033	415	34.0
	10	369	105	34.0
B3	1	894	275	37.4
	2	961	305	37.4
	3	916	335	37.4
	4	916	245	37.4
	5	916	215	37.4
	6	782	185	37.4
	7	894	225	37.4
	8	894	225	37.4
	9	849	225	37.4
B4	1	916	275	39.0
	2	872	305	39.0
	3	849	335	39.0
	4	782	245	39.0
	5	760	215	39.0
	6	693	185	39.0
	7	827	225	39.0
	8	849	275	39.0
	9	872	275	39.0
	10	402	275	39.0

Table 8. Drop-size Distributions for UN Spray Trials.

Drop-size Category	Mass Fraction	Mean Drop Diameter (μm)
	Trial 1-5	
1	0.0080	17.0
2	0.1650	29.7
3	0.3020	46.7
4	0.3960	64.2
5	0.0820	82.1
6	0.0333	100.4
7	0.0097	119.1
8	0.0034	138.3
	Trial 1-6	
1	0.0075	25.2
2	0.0995	37.4
3	0.2020	53.3
4	0.2720	69.2
5	0.1560	85.1
6	0.1140	100.9
7	0.0769	116.7
8	0.0363	132.4
9	0.0283	148.1
10	0.0059	163.6
11	0.0013	179.0
	Trial 1-7	
1	0.0103	25.2
2	0.1170	37.4
3	0.3330	53.3
4	0.2740	64.2
5	0.1390	85.1
6	0.0747	100.9
7	0.0274	116.7
8	0.0079	132.4
9	0.0156	148.1
	Trial 2-2R	
1	0.0098	17.0
2	0.0955	29.7
3	0.3360	46.7
4	0.3350	64.2
5	0.1220	82.1
6	0.0675	100.4
7	0.0257	119.1
8	0.0097	138.3

Table 8. Drop-size Distributions for UN Spray Trials (Cont'd).

Drop-size Category	Mass Fraction	Mean Drop Diameter (μm)
	Trial 2-3	
1	0.0150	17.0
2	0.1820	29.7
3	0.4090	46.7
4	0.3190	64.2
5	0.0438	82.1
6	0.0312	100.4

Table 9. Drop-Size Distribution for Program WIND Spray Trials.

		C-130		Helicopter	
Drop-Size Category	Mass Fraction	Drop Lower Limit (μm)	Drop Upper Limit (μm)	Drop Lower Limit (μm)	Drop Upper Limit (μm)
1	0.001	83	93	96	107
2	0.009	93	105	107	119
3	0.020	105	114	119	134
4	0.030	114	120	134	148
5	0.040	120	127	148	166
6	0.100	127	142	166	211
7	0.100	142	152	211	254
8	0.100	152	162	254	290
9	0.200	162	188	290	393
10	0.100	188	200	393	449
11	0.100	200	219	449	504
12	0.100	219	258	504	602
13	0.040	258	270	602	639
14	0.030	270	278	639	666
15	0.020	278	311	666	697
16	0.010	311	390	697	725

Table 10. Tree Widths by Height in the Program WIND Spray Trials.

Height Above Ground (m)	Tree Width (m)		
	Ponderosa Pine	Incense Cedar	Woody Ground Cover
1	0.40	0.26	0.15
2	0.40	0.26	3.00
3	0.40	3.00	2.00
4	0.40	3.00	1.00
5	0.40	3.00	
6	0.78	3.00	
7	1.16	3.00	
8	1.54	3.00	
9	1.92		
10	2.30		
11	2.68		
12	3.06		
13	3.44		
14	3.82		
15	4.20		
16	3.76		
17	3.33		
18	2.89		
19	2.46		
20	2.02		
21	1.58		
22	1.15		
23	0.71		
24	0.27		

3.2.3 Meteorological Inputs

The FSCBG models are designed to accept the input of wind speed, wind direction, temperature, and relative humidity from multilevel towers in the open and within a canopy. The wind-speed data are fit by a linear least squares regression to equations that describe the wind profiles in the open and within and above a canopy (Bjorklund et al., 1988). These regression equations are then used to determine the above-canopy transport wind speed and wind speeds for four layers within the canopy. The other parameters are averaged within the appropriate layers to provide the required inputs of temperature, relative humidity, and wind direction.

During the UN spray trials, meteorological measurements were made on Tower 00 near the crosswind grid (see Figure 1) and Tower 12 near the inwind grid (see Figure 2). Meteorological data from the appropriate tower for each trial are contained in Table 11. The data represent 10-min averages starting at spray initiation. Tower data were also available during the Program WIND spray trials. Table 12 contains 10-min averages of measurements made on Tower 1 (480 m west of the forest edge) and Tower 2 (110 m inside the forest) near the grid centerline. These data were entered into the model as the open and below-canopy meteorological data.

Measurements of atmospheric turbulence [wind azimuth (σ_A) and elevation (σ_E) angle standard deviations] were made during both sets of trials. Boyle et al. (1975) questioned the representativeness of the turbulence measurements during the UN spray trials. For this reason, the turbulence values used in the models and listed in Table 13 were selected by the FSCBG models using a procedure outlined by Dumbauld and Bowers (1983). The turbulence values used in the model calculations for the Program WIND spray trials, which were from the 30.2-m level of Tower 1, are also listed in Table 13. These values were chosen because FSCBG only calculates dispersion above the canopy. Also, the turbulence measurements made within the forest are unreliable because the wind speed was often near or below the threshold wind speed for the propeller anemometers used on the towers.

3.3 MODEL RESULTS

3.3.1 UN Spray Trials

Figures B.1 through B.10 in Appendix B compare the deposition measurements for the five UN spray trials with the FSCBG2 and FSCBG3 model predictions. As examples of these figures, Figures 4 and 5 show the model results for crosswind Trial 1-5 and Figures 6 and 7 show the results for inwind Trial 2-2R. Inspection of Figures 4 and 5 shows that Model 2 (FSCBG2/FSCBG3 with simple wake effects) does the best job of reproducing the observed deposition for crosswind Trial 1-5. The addition of complex wake effects degrades the correspondence between predictions and measurements, especially within the first kilometer downgrid. The minimum that occurs at 500 meters downgrid in the profile calculated by FSCBG3 with complex wake effects (Model 4), but not in the profile calculated by FSCBG2 with complex wake effects (Model 3), is probably related to differences in the models' transition points from the AGDISP wake effects algorithms to the FSCBG dispersion algorithms. The secondary maximum found in the measurements and predictions at 6-10 kilometers downgrid is explained by the deposition of small drops initially mixed upward to the top of the surface mixing layer (see Dumbauld et al., 1976). This experiment is one of the few in which this phenomena could be observed because a significant fraction of the mass was contained in sufficiently small drops and deposition was sampled far enough downwind. Figures 6 and 7 show that all four model versions yield almost identical results that closely match the deposition measured on either side of the flight line for inwind trial 2-2R. Taken together, the results in Figures 4 through 7 suggest that aircraft wake effects were relatively unimportant for Trial 1-5. The results for the remaining UN spray trials are qualitatively similar.

Table 11. Meteorological Tower Data for the UN Spray Trials.

Tower	Height (m)	Wind Speed ($m\ s^{-1}$)	Wind Direction (deg)
		Trial 1-5	
00	2	1.9	325
	16	2.6	326
	32	2.6	319
	64	2.8	322
	80	2.7	327
	96	2.5	321
		Trial 1-6	
00	2	0.9	003
	16	0.9	318
	32	0.9	301
	64	0.9	298
	80	1.1	304
	96	0.9	294
		Trial 1-7	
00	2	1.3	302
	16	1.8	308
	32	1.8	307
	64	1.8	305
	80	1.8	311
	96	1.5	306
		Trial 2-2R	
12	2	2.5	300
	16	3.3	295
	32	3.2	331
		Trial 2-3	
12	2	3.5	314
	16	4.5	311
	32	4.6	319

Table 12. Program WIND Meteorological Measurements from Towers 1 and 2.

Tower	Height (m)	Trial A-1 Wind Speed ($m\ s^{-1}$)	Trial A-1 Wind Direction (deg)	Trial A-2 Wind Speed ($m\ s^{-1}$)	Trial A-2 Wind Direction (deg)	Trial A-3 Wind Speed ($m\ s^{-1}$)	Trial A-3 Wind Direction (deg)
	2.4	1.0	122	0.9	106	1.8	190
	4.9	1.2	126	1.3	107	1.9	192
	9.7	1.2	127	2.0	106	2.1	192
1	14.3	1.3	127	2.5	105	2.2	195
(open)	19.2	1.3	130	2.8	109	2.2	196
	24.1	1.3	132	2.7	114	2.2	201
	27.1	1.4	133	2.6	118	2.3	201
	30.2	1.3	135	2.5	125	2.4	206
	2.4	0.2	096	0.5	090	0.6	188
	4.9	0.1	130	0.5	091	0.5	187
	8.1	0.1	128	0.6	090	0.4	187
2	13.4	0.0	107	0.6	090	0.2	186
(forest)	18.2	0.1	118	0.9	096	0.3	186
	23.2	0.4	133	1.7	106	0.7	191
	26.2	0.6	138	2.1	106	1.1	193
	28.4	0.7	145	2.4	113	1.3	193

Table 12. Program WIND Meteorological Measurements from Towers 1 and 2 (Cont'd).

Tower	Height (m)	Trial A-4 Wind Speed ($m\ s^{-1}$)	Trial A-4 Wind Direction (deg)	Trial A-5 Wind Speed ($m\ s^{-1}$)	Trial A-5 Wind Direction (deg)	Trial A-6 Wind Speed ($m\ s^{-1}$)	Trial A-6 Wind Direction (deg)
	2.4	1.0	095	1.9	131	1.0	103
	4.9	1.3	098	2.0	138	1.0	111
	9.7	1.8	101	2.2	137	1.5	109
1	14.3	2.1	099	2.4	136	1.9	105
(open)	19.2	2.3	097	2.6	136	2.4	106
	24.1	2.4	095	2.7	138	2.5	106
	27.1	2.3	094	2.8	139	2.4	110
	30.2	2.8	095	2.8	140	2.6	116
	2.4	0.4	088			0.4	091
	4.9	0.2	089			0.5	094
	8.1	0.3	087			0.5	090
2	13.4	0.5	078	ND[a]		0.5	091
(forest)	18.2	0.9	080			0.9	096
	23.2	1.4	079			1.7	102
	26.2	1.6	080			2.1	102
	28.4	1.8	083			2.3	108

Table 12. Program WIND Meteorological Measurements from Towers 1 and 2 (Cont'd).

Tower	Height (m)	Trial B-1		Trial B-2		Trial B-3	
		Wind Speed ($m\ s^{-1}$)	Wind Direction (deg)	Wind Speed ($m\ s^{-1}$)	Wind Direction (deg)	Wind Speed ($m\ s^{-1}$)	Wind Direction (deg)
	2.4	3.0	161	7.3	170	1.9	104
	4.9	3.2	169	7.7	168	2.2	110
	9.7	3.7	170	8.8	164	2.6	111
1	14.3	3.9	171	9.3	165	2.9	108
(open)	19.2	4.0	169	9.5	164	3.2	108
	24.1	4.1	168	9.7	157	3.4	108
	27.1	4.2	168	10.0	151	3.4	109
	30.2	4.2	168	10.0	152	4.0	114
	2.4	0.7	178	1.6	170	0.2	102
	4.9	0.7	177	1.8	168	0.2	098
	8.1	0.7	176	1.6	164	0.4	087
2	13.4	0.4	179	1.0	165	0.6	088
(forest)	18.2	0.5	178	1.3	164	1.1	096
	23.2	1.1	170	2.7	157	1.6	095
	26.2	1.9	161	4.2	151	1.9	095
	28.4	2.6	160	5.6	152	2.1	097

Table 12. Program WIND Meteorological Measurements from Towers 1 and 2 (Cont'd).

		Trial B-4	
Tower	Height (m)	Wind Speed ($m\ s^{-1}$)	Wind Direction (deg)
	2.4	1.4	094
	4.9	1.5	104
	9.7	1.7	112
1	14.3	1.5	117
(open)	19.2	1.4	123
	24.1	1.2	129
	27.1	1.0	139
	30.2	0.8	158
	2.4	0.5	091
	4.9	0.3	090
	8.1	0.2	091
2	13.4	0.3	094
(forest)	18.2	0.4	104
	23.2	0.5	108
	26.2	0.6	112
	28.4	0.6	120

Table 13. Turbulence Inputs.

Trial	Turbulence Intensity σ_A (deg)	Turbulence Intensity σ_E (deg)
	UN Spray Trials	
1-5	18.5	6.8
1-6	18.0	6.6
1-7	16.8	6.2
2-2R	17.3	6.4
2-3	15.4	6.0
	Program WIND Spray Trials	
A-1	5.6	4.0
A-2	6.1	4.3
A-3	9.1	5.7
A-4	7.6	2.3
A-5	5.6	2.8
A-6	3.4	1.7
B-1	10.3	6.6
B-2	10.8	6.5
B-3	5.0	2.9
B-4	13.2	6.2

3.3.2 Program WIND Forest Spray Trials

Figures B.11 through B.30 in Appendix B compare the deposition measurements for the ten Program WIND forest spray trials with the FSCBG2 and FSCBG3 model predictions. Examples of these figures are shown in Figures 8 and 9 for inwind (C-130) Trial A-3 and in Figures 10 and 11 for crosswind (C-130) Trial A-4. Figures 8 through 11 illustrate the tendency for the Kromekote™ deposition estimates to exceed the corresponding Mylar™ estimates in areas of high deposition and to be lower than the Mylar™ estimates in areas of low deposition. This tendency is further discussed in Section 4. The results in Figures 8 and 9 for inwind Trial A-3 show that FSCBG2 or FSCBG3 with complex wake effects (Model 3 or 4) better fits the measured deposition peak than FSCBG2/FSCBG3 with no wake effects or simple wake effects (Model 1 or 2). In this case, the model with no or simple wake effects predicts a peak that is too large and too narrow. In contrast, Figures 10 and 22 show that the model with no or simple wake effects best fits the measured deposition peak for crosswind Trial A-4. However, either FSCBG2 or FSCBG3 with complex wake effects provides a better fit to the deposition measured at the longer downgrid distances than FSCBG2/FSCBG3 with no or simple wake effects. As in the case of the crosswind UN spray trials, the differences between the FSCBG2 and FSCBG3 predictions with complex wake effects appear to be due to differences in the models' transition points from the AGDISP wake effects algorithms to the FSCBG dispersion algorithms.

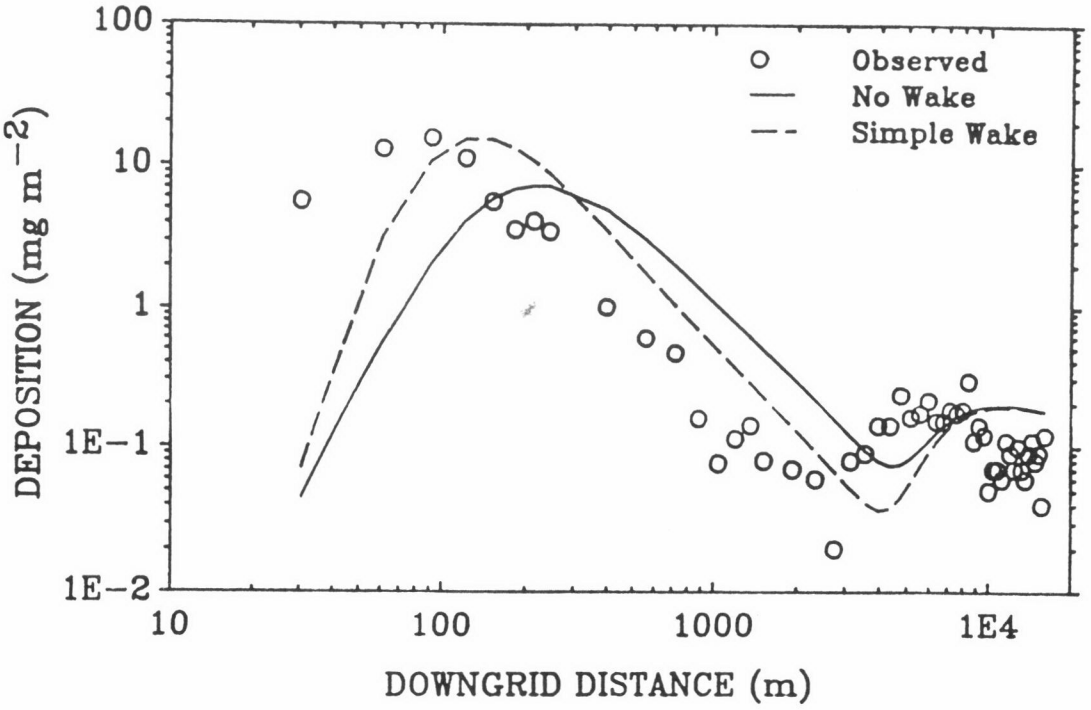

Figure 4. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with no Wake Effects (Model 1) and Simple Wake Effects (Model 2) for UN Spray Trial 1-5.

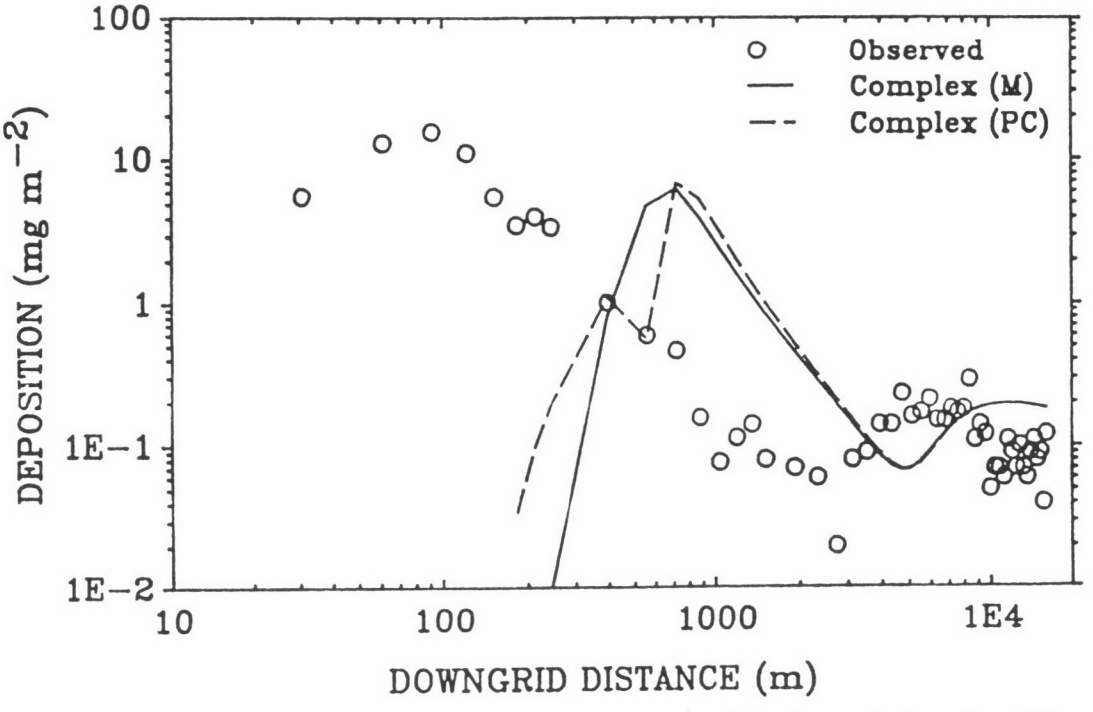

Figure 5. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for UN Spray Trial 1-5.

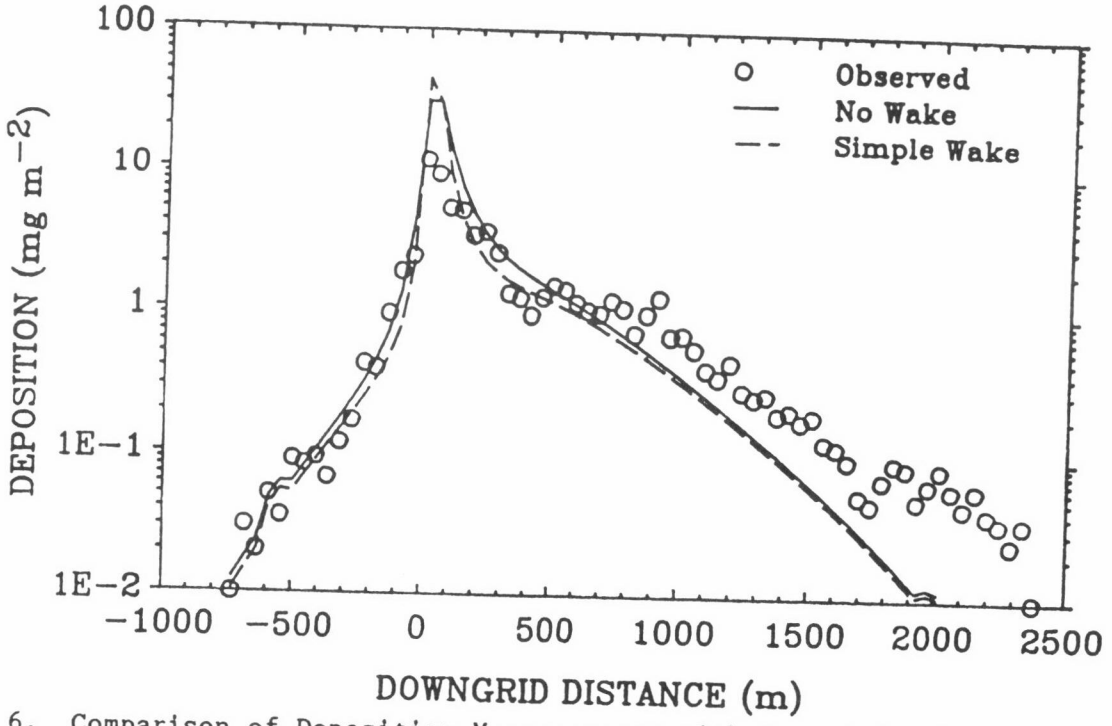

Figure 6. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with no Wake Effects (Model 1) and Simple Wake Effects (Model 2) for UN Spray Trial 2-2R.

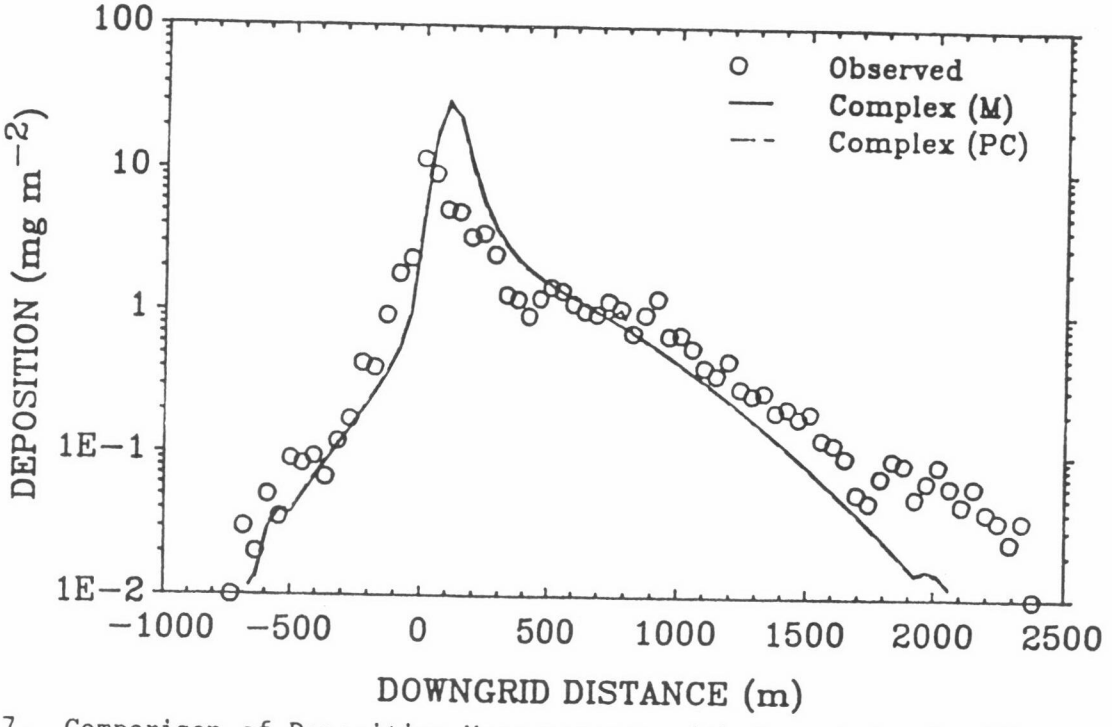

Figure 7. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for UN Spray Trial 2-2R.

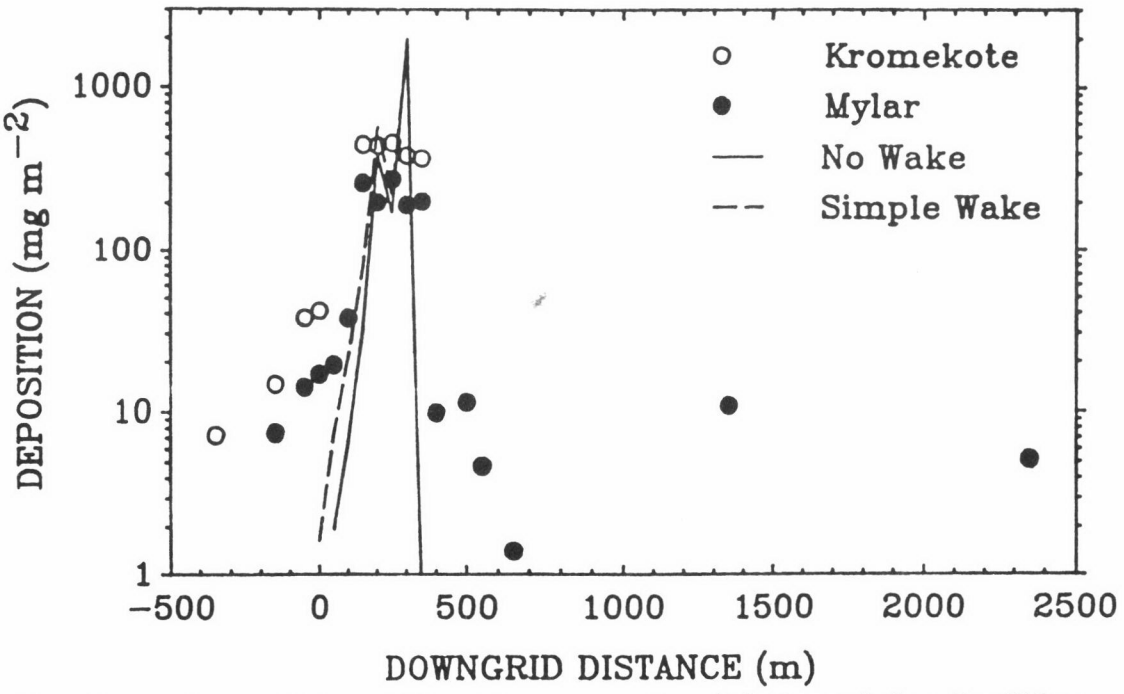

Figure 8. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with no Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial A-3.

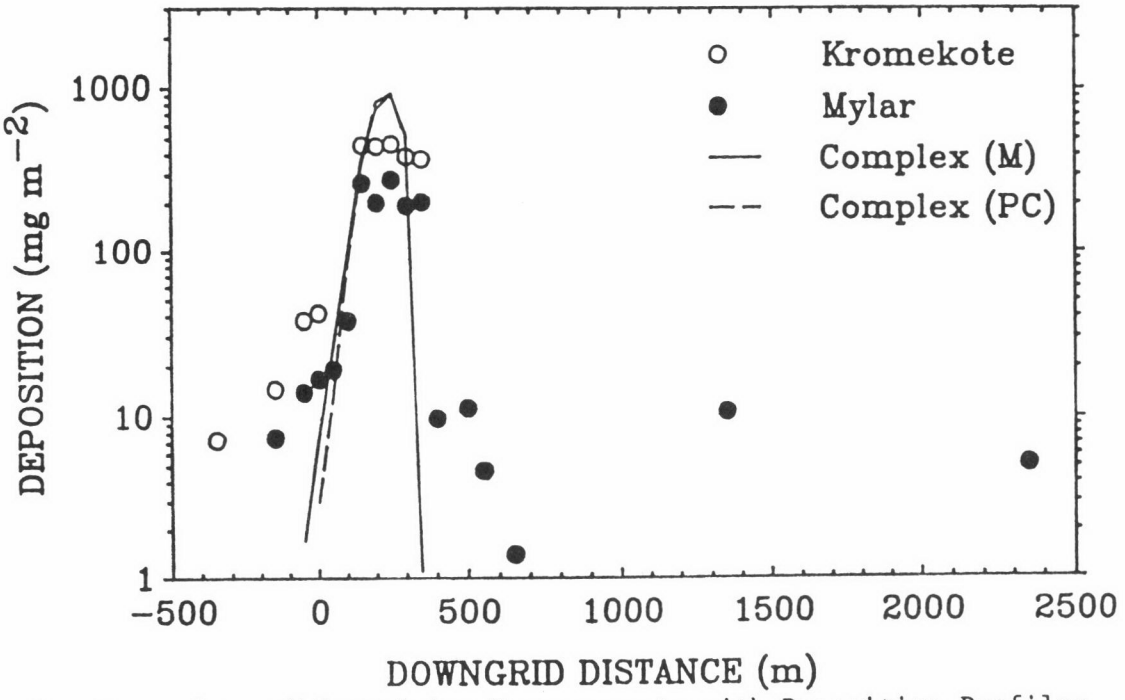

Figure 9. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial A-3.

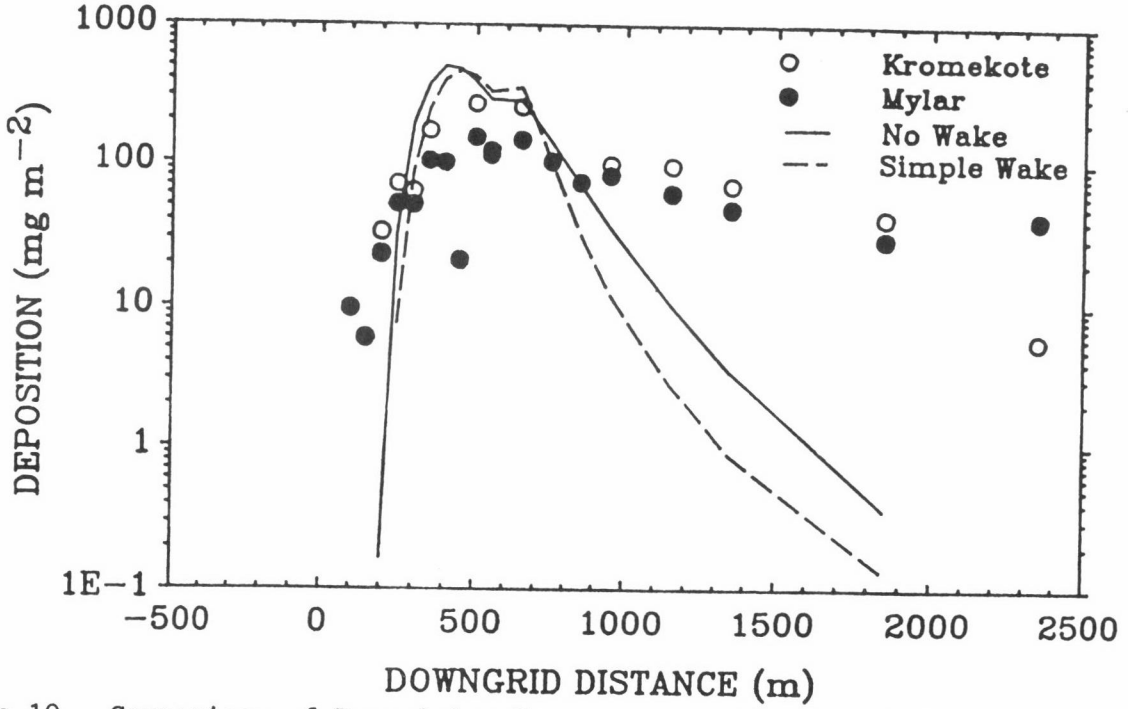

Figure 10. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with no Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial A-4.

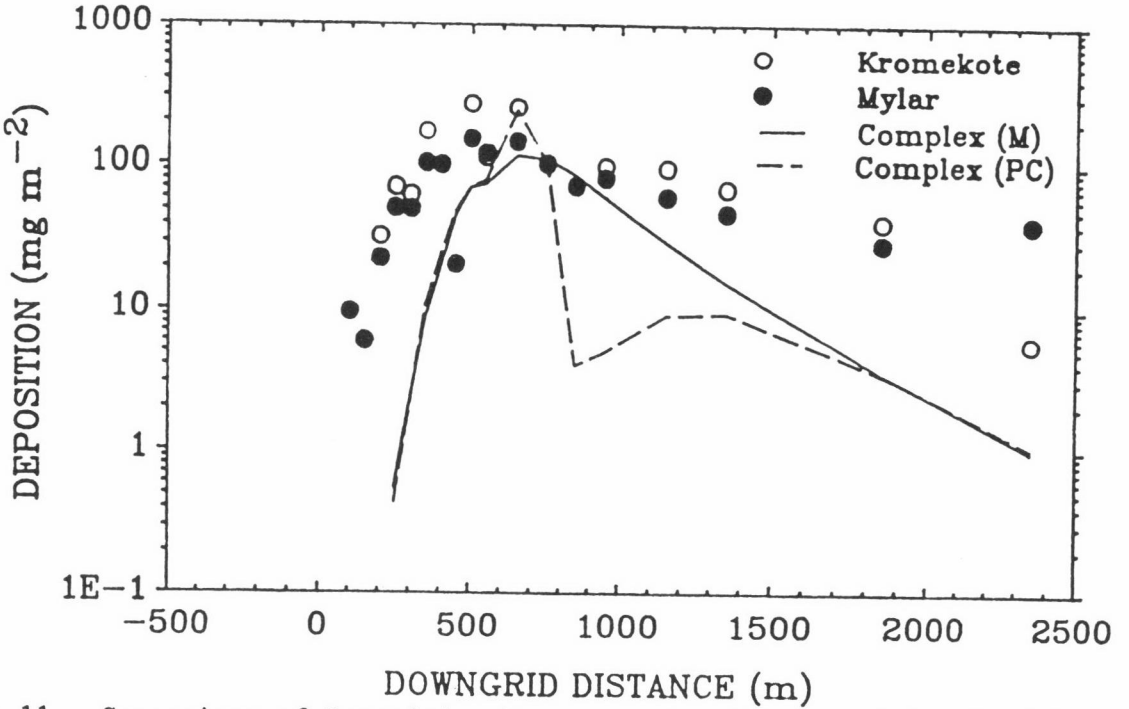

Figure 11. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial A-4.

Figures 12 and 13 illustrate model results for the inwind helicopter Trial B-2, while Figures 14 and 15 illustrate model results for the crosswind helicopter Trial B-3. Comparison of Figures 12 through 15 with Figures 8 through 11 shows that the results for the helicopter releases are qualitatively similar to the results for the C-130 releases. That is, the addition of complex wake effects to either FSCBG2 or FSCBG3 results in the best correspondence between predictions and measurements for the inwind release as well as for the crosswind release at the longer downgrid distances. One possible interpretation of these results is that aircraft wake vortices have the greatest influences on drop trajectories for inwind releases. This hypothesis is supported by the fact that the persistence of aircraft vortices increases as the crosswind component of the mean wind decreases. The fact that the inclusion of complex wake effects in the model calculations for the crosswind trials appears to improve the correspondence between predictions and measurements at the longer downwind distances where deposition is determined by the smaller drops is possibly explained by the fact that aircraft wake vortices have a greater influence on the initial trajectories of the smaller drops than on the trajectories of the larger drops. If these interpretations of the model results are correct, it is likely the complex wake effects option of FSCBG2 and FSCBG3 overestimate the impact of aircraft wake vortices on the initial trajectories of large drops with a crosswind release, but not necessarily with an inwind release.

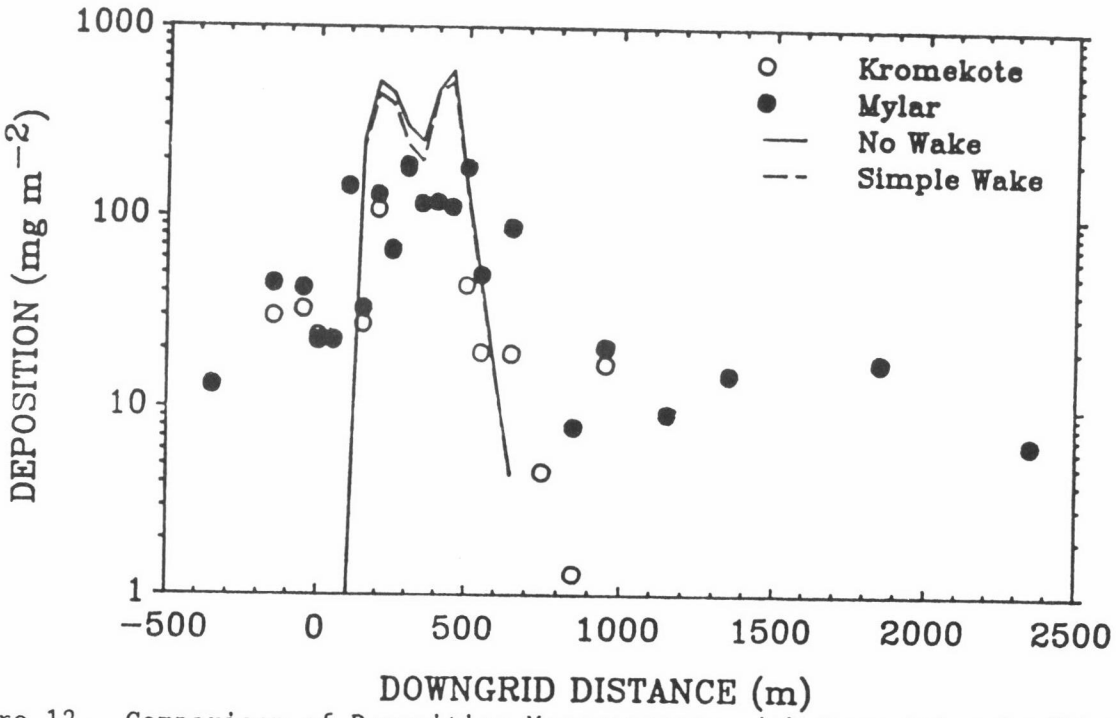

Figure 12. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with no Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial B-2.

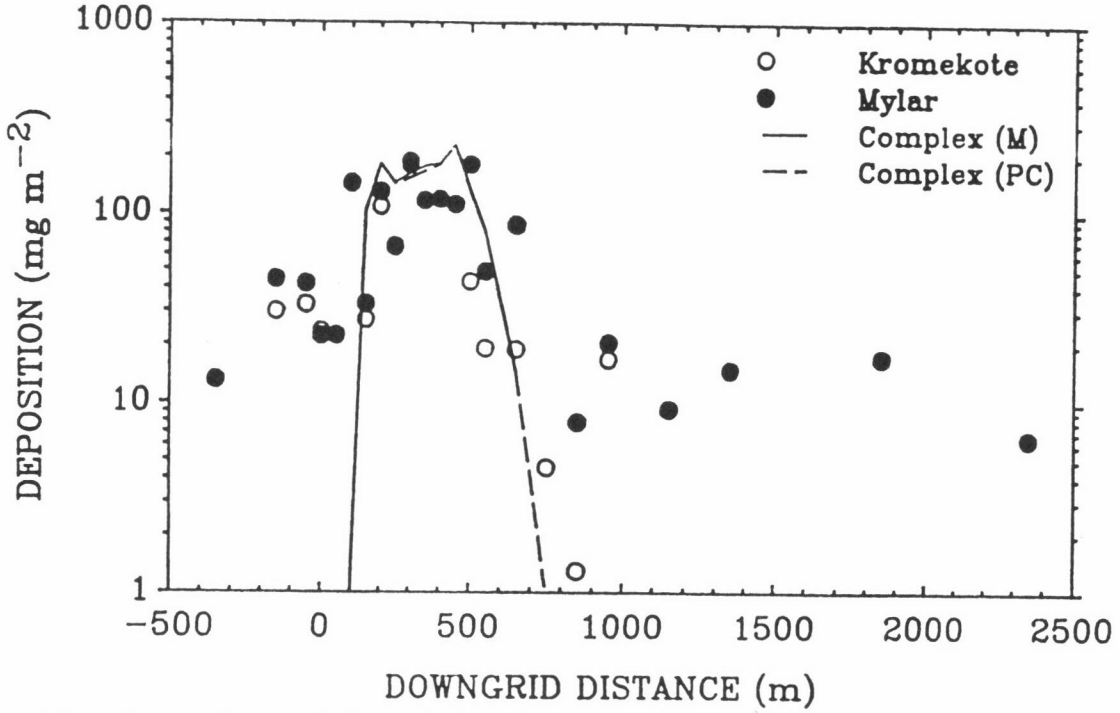

Figure 13. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial B-2.

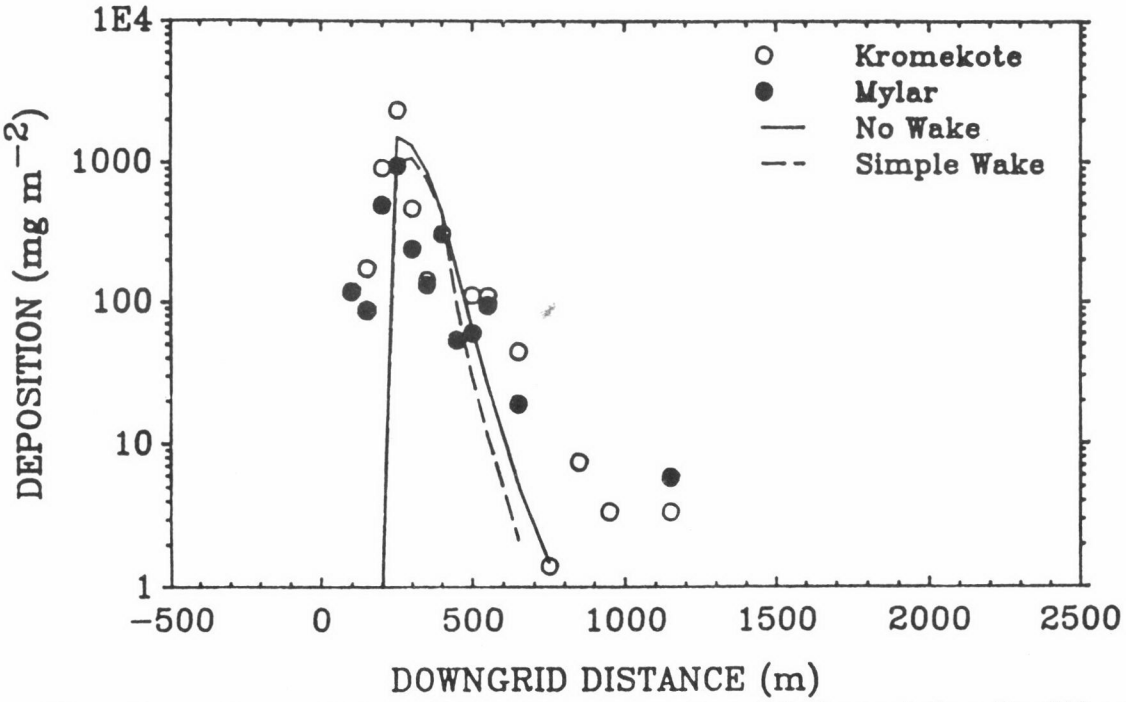

Figure 14. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with no Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial B-3.

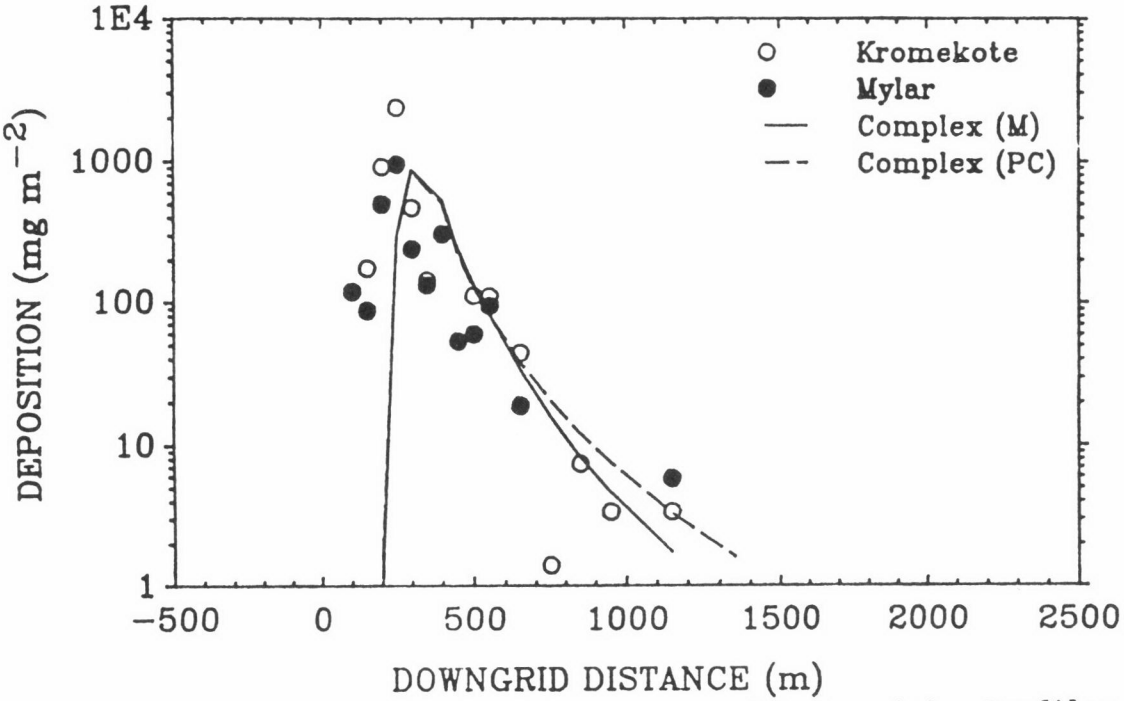

Figure 15. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial B-3.

SECTION 4. ANALYSIS AND CONCLUSIONS

4.1 STATISTICAL ANALYSIS

We used the statistical analysis software described by Hanna (1989) to evaluate and intercompare the various versions of the FSCBG2 and FSCBG3 models identified by model number in Section 1. The two measures of model performance used by this software are the fractional bias FB and the normalized mean square error NMSE. These performance measures are defined as

$$FB = (\bar{C}_o - \bar{C}_p)/0.5\ (\bar{C}_o + \bar{C}_p) \quad (1)$$

$$NMSE = \overline{(C_o - C_p)^2}/\bar{C}_o\ \bar{C}_p \quad (2)$$

where C_o represents an observation, C_p represents a prediction, and the overbar indicates an average. Both FB and NMSE are equal to zero if there is perfect agreement between model predictions and measurements.

Of the various resampling procedures available in the Hanna (1989) statistical analysis software, we selected the "moment bootstrap" to calculate 95-percent confidence limits on the FB and NMSE as well as on their differences between model pairs. To illustrate this technique, assume that the FB or NMSE is calculated for a set of N pairs of observed and predicted deposition values. A new set of N paired values is randomly drawn (with replacement) from the original set. That is, if a given pair C_o/C_p is drawn, it is replaced before the next draw is made. The FB or NMSE is then computed for the new set of N pairs. This resampling procedure is repeated a large number of times (1000 in this study). Next, the resampled values of the FB or NMSE are used to calculate the mean and the variance of the FB or NMSE, and these are used with the Student's-t procedure to estimate the 95-percent confidence limits for N-1 degrees of freedom.

The results of the statistical analyses for the UN spray trials are summarized in Tables 14 through 17. As shown by Table 14, the absolute value of the FB ranges from 0.12 for Model 4 (FSCBG3 with complex wake effects) to 0.32 for Model 2 (FSCBG2/FSCBG3 with simple wake effects). For comparison, a mean difference between observations and predictions of 50 percent results in an FB of 0.4, while a factor of two difference results in an FB of 0.67. Given representative source and meteorological inputs, a factor of two accuracy has traditionally been assigned to the results of dispersion model calculations (Fox, 1981). Thus, all four versions of the FSCBG model yield results that are, on average, within the state of the art. Table 16 shows that the differences between the FBs calculated by the four models are significant at the 95-percent confidence level only for Models 2 and 3. Table 15 shows that Model 4 has the smallest NMSE as well as the smallest FB. That is, it has the smallest average difference between predictions and observations. Model 2 (FSCBG2/FSCBG3 with simple wake effects) has the largest NMSE, but Table 17 shows that its NMSE does not differ significantly from the NMSE for Model 4.

Table 14. Summary of Model FBs for the UN Spray Trials.

Model No.	FB[a]	FB 95% Confidence Limits	Model Biased (FB≠0) at 95% Confidence Level?
1	-0.133	-0.61 to 0.36	No
2	-0.323	-0.81 to 0.23	No
3	0.242	-0.18 to 0.62	No
4	0.117	-0.32 to 0.50	No

[a]FB <0 indicates bias toward overestimation and FB >0 indicates bias toward underestimation.

Table 15. Summary of Model NMSEs for the UN Spray Trials.

Model No.	NMSE	NMSE 95% Confidence Limits
1	16.1	8.9 to 24.0
2	18.2	9.0 to 28.0
3	16.2	5.7 to 26.0
4	14.6	5.0 to 24.0

Table 16. Matrix Identifying Combinations of Models Whose FBs Differ at the 95-Percent Confidence Level for the UN Spray Trials.

	Model No. 1	Model No. 2	Model No. 3	Model No. 4
Model No. 1	--	No	No	No
Model No. 2	No	--	Yes	No
Model No. 3	No	Yes	--	No
Model No. 4	No	No	No	--

Table 17. Matrix Identifying Combinations of Models Whose NMSEs Differ at the 95-percent Confidence Level for the UN Spray Trials.

	Model No. 1	Model No. 2	Model No. 3	Model No. 4
Model No. 1	--	No	No	No
Model No. 2	No	--	No	No
Model No. 3	No	No	--	No
Model No. 4	No	No	No	--

The paired deposition measurements from the Program WIND forest spray trials provide some insight into how uncertainty in the deposition measurements can affect apparent model performance. As a consistency check on the deposition measurements, we used the statistical analysis software to calculate the mean normalized differences (FBs) between the paired Kromekote™ card and Mylar™ sheet deposition measurements. As shown by the summary statistics in Table 18, the average deposition measured by the chemical analysis method (Mylar™ sheets) generally was less than the average deposition measured by the drop count sampling method (Kromekote™ cards). The differences between the two sampling methods are statistically significant at the 95-percent confidence level for seven of the ten trials and for all trials combined. The average Kromekote™ card deposition is less than the average Mylar™ sheet deposition for only one of the seven trials with statistically significant differences. The mean FB for all trials combined of 0.44 indicates that, on average, the Mylar™ deposition values were only 64 percent of the Kromekote™ values. Inspection of the individual measurements shows that the Kromekote™ measurements typically exceeded the Mylar™ measurements when the deposition measured by either method exceeded about 100 mg m^{-2} and were less than the Mylar™ measurements when the deposition was smaller.

The results of the statistical analyses for the Program WIND forest spray trials are summarized in Tables 19 through 22. If the Kromekote™ deposition measurements are assumed to be the most representative deposition measurements, the absolute value of the FB ranges from 0.06 for Model 2 to 0.23 for Model 4. The differences in FB between Model 2 and the three other models are all significant at the 95-percent confidence level. Model 2 also has the second lowest NMSE, although the differences between the NMSE for Model 2 and the NMSEs for the other models are not statistically significant. Thus, the statistical results suggest that Model 2 is the model of choice for the Program WIND data set if the Kromekote™ deposition measurements are used.

Substitution of the Mylar™ deposition measurements for the Kromekote™ measurements radically alters any conclusions about the model of choice for the Program WIND forest spray trials. As shown by Table 19, Models 1 and 2 are biased at 95-percent confidence level. Although the hypothesis that Models 3 and 4 are unbiased cannot be rejected at the 95-percent confidence level, the absolute values of their FBs are about 4.5 times larger than the FB for Model 2 with the Kromekote™ deposition measurements. Models 3 and 4 have the smallest NMSEs for the Mylar™ deposition measurements, but they are still larger than the largest NMSEs for the Kromekote™ measurements.

4.2 CONCLUSIONS

In summary, the results of the statistical analyses demonstrate that the FSCBG2 and FSCBG3 models have significant quantitative skill in predicting the deposition measured during the UN and Program WIND spray trials. On average, model performance is within the factor of two accuracy commonly attributed to state-of-the-art dispersion models. Although the complex wake effects options of FSCBG2 and FSCBG3 differ in their transition points from the AGDISP wake effects algorithms to the FSCBG dispersion algorithms, the differences in their performance as measured by the FB and NMSE are not statistically significant at the 95-percent confidence level. As noted in Section 3, the inclusion of complex wake effects in the calculations made by either FSCBG2 or FSCBG3 appears in some cases to improve the correspondence between predictions and

measurements for the Program WIND spray trials over that obtained using the simple wake effects option. Specifically, the inclusion of complex wake effects results in improved agreement between predictions and measurements: (1) near the dissemination line for the inwind trials and (2) at the longer downwind distances for the crosswind trials. This qualitative improvement in model performance probably is not apparent in the model performance statistics because of the uncertainties in the measurements. For example, the mean difference between the paired Kromekote™ and Mylar™ deposition measurements generally exceeds the mean difference between predictions and either set of measurements.

Table 18. Summary of Deposition Differences Between Kromekote™ (Drop Count) and Mylar™ (Chemical Analysis) Sampling Methods for the Program WIND Forest Spray Trials.

Trial No.	FB[a]	FB 95% Confidence Limits	Difference Significant (FB≠0) at 95% Confidence Level?
A-1	-0.115	-0.63 to 0.40	No
A-2	0.187	-0.16 to 0.53	No
A-3	0.604	0.50 to 0.71	Yes
A-4	0.325	0.12 to 0.53	Yes
A-5	0.746	0.55 to 0.94	Yes
A-6	0.704	0.47 to 0.94	Yes
B-1	-0.105	-0.60 to 0.39	No
B-2	-0.314	-0.55 to -0.07	Yes
B-3	0.660	0.39 to 0.93	Yes
B-4	0.774	0.37 to 1.20	Yes
All	0.440	0.31 to 0.57	Yes

[a] FB <0 indicates average Mylar™ sheet deposition exceeds average Kromekote™ card deposition.

Table 19. Summary of Model FBs for the Program WIND Forest Spray Trials.

Model No.	FB[a]	FB 95% Confidence Limits	Model Biased (FB≠0) At 95% Confidence Level?
		Kromekote™ Data	
1	-0.162	-0.43 to 0.11	No
2	-0.064	-0.35 to 0.23	No
3	0.216	-0.13 to 0.56	No
4	0.227	-0.12 to 0.57	No
		Mylar™ Data	
1	-0.600	-0.87 to -0.33	Yes
2	-0.507	-0.79 to -0.22	Yes
3	-0.287	-0.60 to 0.28	No
4	-0.273	-0.59 to 0.40	No

[a]FB <0 indicates bias toward overestimation and FB >0 indicates bias toward underestimation.

Table 20. Summary of Model NMSEs for the Program WIND Forest Spray Trials.

Model No.	NMSE	FB 95% Confidence Limits
	Kromekote™ Data	
1	3.86	1.6 to 6.1
2	4.20	1.5 to 6.9
3	4.77	1.4 to 8.2
4	4.81	1.4 to 8.3
	Mylar™ Data	
1	8.76	5.2 to 12.0
2	8.47	4.5 to 12.0
3	7.25	5.0 to 9.5
4	7.19	5.0 to 9.4

Table 21. Matrix Identifying Combinations of Models Whose FBs Differ at the 95-percent Confidence Level for the Program WIND Forest Spray Trials.

	Model No. 1	Model No. 2	Model No. 3	Model No. 4
		Kromekote™ Data		
Model No. 1	--	Yes	Yes	Yes
Model No. 2	Yes	--	Yes	Yes
Model No. 3	Yes	Yes	--	No
Model No. 4	Yes	Yes	No	--
		Mylar™ Data		
Model No. 1	--	No	No	No
Model No. 2	No	--	Yes	No
Model No. 3	No	Yes	--	No
Model No. 4	No	No	No	--

Table 22. Matrix Identifying Combinations of Models Whose NMSEs Differ at the 95-percent Confidence Level for the Program WIND Forest Spray Trials.

	Model No. 1	Model No. 2	Model No. 3	Model No. 4
		Kromekote™ Data		
Model No. 1	--	No	No	No
Model No. 2	No	--	No	No
Model No. 3	No	No	--	No
Model No. 4	No	No	No	--
		Mylar™ Data		
Model No. 1	--	No	No	No
Model No. 2	No	--	No	No
Model No. 3	No	No	--	No
Model No. 4	No	No	No	--

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SECTION 5. APPENDICES

APPENDIX A. DESCRIPTION OF THE FSCBG2 AND FSCBG3 MODELS

The major components of FSCBG2/FSCBG3 are the aircraft wake module, the drop evaporation module, the canopy penetration module, and the dispersion/deposition module. The user may select any or all of these modules as required by a specific modeling problem. A brief description of the technical basis for each module is given below. The nomenclature used in this discussion is defined in Table A-1.

A.1 AIRCRAFT WAKE MODULE

When spray material is released from an aircraft, it is immediately engulfed in the vortices produced by the wings and propellers of a fixed-wing aircraft or by the rotor of a rotary-wing aircraft. Because the initial aerodynamic force on spray drops exceeds that of gravity, the drops are transported by the wake flow field, which can be represented by a pair of vortices. FSCBG2/FSCBG3 have two aircraft wake options. In the simple wake option, the sink rate ω of the vortex system is given by (Prandtl and Tietjens, 1934)

$$\omega = \frac{8gw_a}{\pi^3 \rho_A b^2 v_a} \qquad \text{(A-1)}$$

where g is the acceleration due to gravity, w_a is the aircraft mass, ρ_A is the air density, b is the aircraft wing span, and v_a is the aircraft speed. Although Equation (A-1) is strictly applicable to fixed-wing aircraft, helicopter vortices resemble fixed-wing vortices at high forward speeds. The simple aircraft wake option assumes that the vortex tube stops sinking at a height b/2 above the surface or the canopy top (Jones, 1970). The dispersion/deposition module of FSCBG2/FSCBG3 describes the transport of drops below b/2.

The complex aircraft wake option of FSCBG2/FSCBG3 incorporates the AGDISP code, which assumes an aircraft in level flight releasing drops into a plane normal to the flight direction. As discussed by Bilanin et al. (1989), AGDISP uses the Lagrangian equations of motion to predict the mean trajectories and standard deviations about the means of drops released from specific nozzle positions along the spray boom. AGDISP also considers the effects of drop evaporation on their trajectories. FSCBG2 and FSCBG3 differ slightly in the point at which drops are transferred from AGDISP to the dispersion/deposition module. FSCBG2 uses AGDISP until drops deposit or the wake decays to the level of background atmospheric turbulence. FSCBG3 uses AGDISP until drops deposit or a user-specified drop transport time is exceeded.

TABLE A.1. Definition of Nomenclature.

Symbol	Definition
A_j, B_j, C_j	Coefficients in quadratic equation describing the diameter of the jth drop size as a function of time
b	aircraft wing span
d_v	molecular diffusivity of the spray material in vapor form
D_j	diameter of drop in jth drop-size category
DEP	deposition
DEP_{cwi}	crosswind-integrated deposition
DOS_L	dosage produced by a line source
DOS_p	dosage produced by a point source
e_s	partial pressure of the evaporating vapor at the spray drop surface
e_∞	partial pressure of the evaporating vapor an infinite distance from the spray drop
E	tree element collection efficiency
f_k	probability of a drop encountering a tree envelope in the kth canopy layer
f_v	ventilation factor for drop evaporation
F_k	fractional part of f_k
g	acceleration due to gravity
H	spray release height
H'	effective spray release height due to drop settling
H_c	canopy height
I_k	integer part of f_k
K	constant in the equation for drop evaporation
L	length of line source

TABLE A.1. Definition of Nomenclature (Cont'd).

Symbol	Definition
L_k	average length of drop trajectory through cylinder representing the average tree in the kth canopy layer
M_1	molecular weight of the spray material
M_m	molecular weight of the air-spray vapor mixture
N_t	number of trees along a drop trajectory
p	atmospheric pressure
P	probability that drop impacts on a tree element
P_k	probability that drop impacts on a tree element in the kth canopy layer
P_p	probability of drop penetration for a horizontal trajectory
P_{Tk}	probability that a drop penetrates the kth canopy layer
Q_o	spray source strength in mass for a point source
R,R'	random numbers between 0 and 1
t	time after spray dissemination
u_k	mean wind speed in kth canopy layer
v	drop settling velocity
v_a	aircraft flight speed
w_a	aircraft mass
W_k	tree diameter in kth canopy layer
W_m	maximum tree diameter
x,y,z	downwind, crosswind, vertical distances
α	probability of penetration correction factor for a non-horizontal drop trajectory
γ	surface reflection coefficient

TABLE A.1. Definition of Nomenclature (Cont'd).

Symbol	Definition
δ	fraction of drops deposited between release point and downwind distance x
Δt	time increment
Δx_t	average tree spacing
Δz_k	height of kth canopy layer
ϕ_k	declination of drop trajectory below plane of the horizon in kth canopy layer
ρ_A	air density
ρ_l	density of the liquid spray material
ρ_t	tree density in number per unit area
$\sigma_x, \sigma_y, \sigma_z$	standard deviations of alongwind, crosswind, and vertical concentration distributions
ω	vortex sink rate
χ_L	concentration produced by a line source
χ_p	concentration produced by a point source

A.2 EVAPORATION MODULE

Evaporation can significantly alter the drop-size distribution as a spray cloud descends from the aircraft and is transported through the atmosphere. Evaporation causes drop diameters to decrease with time at an increasing rate, which in turn causes drop settling velocities to decrease at an increasing rate. Consequently, the net effect of evaporation is to decrease deposition near the release line and increase the downwind drift of spray drops and evaporated, gaseous spray material (vapor). FSCBG2/FSCBG3 can consider an evaporating (volatile) spray material or a spray mixture of volatile and non-volatile components. The models retain FSCBG's two evaporation options. The diameter D_j of a drop in the jth drop-size category at time t after release is given by the quadratic equation

$$D_j(t) = A_j + B_j t + C_j t^2 \qquad \text{(A-2)}$$

In the first evaporation option the user enters the coefficients A_j, B_j, and C_j. In the second evaporation option, FSCBG2/FSCBG3 calculate the coefficients in Equation (A-2) from theoretical relationships.

The diameter of a drop in the jth size category after time increment Δt is

$$D_j(\Delta t) = D_j(0) + \frac{dD_j}{dt}\Delta t \qquad \text{(A-3)}$$

where $D_j(0)$ is the drop diameter at the start of the time increment. According to Fuchs (1959), Frossling defines the time rate of change of drop diameter by

$$\frac{dD_j}{dt} = \frac{KM_1 d_v \rho_A (e_s - e_\infty) f_v}{M_m D_j \rho_l (p - e_s)} \qquad \text{(A-4)}$$

where K is a constant, M_1 is the molecular weight of the liquid, d_v is the molecular diffusivity of the spray material in vapor form, ρ_A is the air density, ρ_l is the density of the spray material in liquid form, e_s is the partial pressure of the evaporating vapor at the spray drop surface, e_∞ is the partial pressure of the evaporating vapor an infinite distance from the spray drop, p is the atmospheric pressure, and f_v is a dimensionless ventilation factor. M_m, the molecular weight of the air-vapor mixture, is approximated in the model by the molecular weight of air. Equations (A-3) and (A-4) are used to calculate the drop diameter versus time until the drop evaporates to a diameter of 5 μm or a settling velocity less than 0.02 m s^{-1}, whichever requires the longest time. The coefficients in Equation (A-2) are then obtained from a logarithmic least-squares regression fit of these results.

A.3 CANOPY PENETRATION MODULE

The canopy penetration module calculates the number of drops reaching a given height within the canopy, or the ground beneath the canopy, by considering losses of material due to impaction on vegetative elements. Canopy penetration is calculated using either the Grim and Barry (1975) Monte Carlo technique or the analytic technique developed by Bjorklund et al. (1988). Although both options yield equivalent results, the analytic canopy penetration routine requires much less computer execution time.

In the Monte Carlo canopy penetration approach, a large number of drops (on the order of 1000) in each drop-size category are passed along the drop trajectory through a simulated canopy, which is divided into four equal layers. For a given drop size, the downwind distance of the drop when it reaches the bottom of the kth height interval is given by

$$x_k = \frac{(2k-1)H_c}{4\tan\phi_k} \qquad \text{(A-5)}$$

where H_c is the canopy height and ϕ_k is the declination of the drop trajectory below the plane of the horizon in the kth layer. This angle is defined as

$$\phi_k = \arctan (v/u_k) \tag{A-6}$$

where v is the drop's settling velocity and u_k is the mean wind speed in the kth layer. In the absence of drop impaction, the number of trees along the drop's trajectory is given by the expression

$$N_t = \frac{x_k}{\Delta x_t} \tag{A-7}$$

The maximum horizontal travel distance x_4 is obtained from Equation (A-5) with k equal to 4, while the average tree spacing Δx_t is based on the tree density (stems per unit area). The downwind and crosswind coordinates of the nth tree are randomized by the expressions

$$x_n = (N_t - n + R - 0.5)\ \Delta x_t \tag{A-8}$$

$$y_n = |R' - 0.5|\ \Delta x_t \tag{A-9}$$

with R and R' obtained from random numbers between 0 and 1.

The possibility of a drop trajectory intersecting a tree envelope at the height where its trajectory passes through the downwind distance x_n is determined by comparing the crosswind distance y_n with the average tree radius at that height. If y_n is greater than the average tree radius, no intersection occurs and the algorithm proceeds to the next tree along the trajectory. If the drop trajectory intersects the tree envelope, the probability that the drop impacts on a tree element is calculated from the relationship

$$P = E\ (1 - P_p^{\alpha}) \tag{A-10}$$

where E is the collection efficiency, P_p is the probability of penetration for a horizontal trajectory, and α is a correction factor for a non-horizontal trajectory. This correction is

$$\alpha = \begin{cases} \dfrac{1}{\cos \phi_k} & ; \quad \dfrac{1}{\cos \phi_k} \leq \dfrac{H_c}{W_m} \\ \dfrac{H_c}{W_m} & ; \quad \dfrac{1}{\cos \phi_k} > \dfrac{H_c}{W_m} \end{cases} \tag{A-11}$$

where W_m is the maximum width of the tree envelope.

In the analytic canopy penetration algorithm, the height of the canopy is divided into ten layers and an average tree diameter is entered for each layer. Each tree is represented in the kth layer by a cylinder of diameter W_k and height Δz_k. The average length of a drop trajectory through this cylindrical envelope is

$$L_k = \frac{\pi W_k \Delta z_k (u_k^2 + v^2)^{1/2}}{(4\Delta z_k u_k + \pi W_k v)} \qquad \text{(A-12)}$$

In the limit that the mean wind speed u_k goes to zero, L_k equals Δz_k. Similarly, in the limit that the settling velocity v goes to zero, L_k equals $\pi W_k/4$, which is the mean horizontal path length through a circle of diameter W_k. The correction factor α is then defined as $L/(\pi W_k/4)$, which is the number of mean horizontal path lengths traversed by the inclined drop trajectory while penetrating the cylindrical tree.

The analytic canopy penetration algorithm assumes that the probability of a drop encountering a randomly placed tree envelope is equal to the fraction of the horizontal area effectively occupied by trees. If u_k is zero and the drops fall vertically, this probability is simply the fraction of the horizontal area occupied by trees. This fraction must be increased to account for horizontal drop transport if u_k is nonzero. The increase in the effective horizontal area of a single tree is given by the product of W_k and the downwind distance a drop travels while falling through Δz_k. The resulting probability of encountering a tree envelope is

$$f_k = \left(\frac{\pi W_k^2}{4} + \frac{u_k W_k \Delta z_k}{v} \right) \rho_t \qquad \text{(A-13)}$$

where ρ_t is the tree density (number per unit area). Note that it is possible for f to exceed unity. The overall probability of a drop penetrating a layer is given by

$$P_{Tk} = [1 - F_k (1-P_k)] P_k^{I_k} \qquad \text{(A-14)}$$

where P_k is from Equation (A-10), while I_k and F_k are the integer and fractional parts of f_k, respectively. For example, if f_k equals 2.4, I_k equals 2 and F_k equals 4. In this case, six tenths of the drops penetrate two trees and the remaining four tenths penetrate three trees.

A.4 DISPERSION/DEPOSITION MODULE

The dispersion/deposition module is based on steady-state Gaussian dispersion model concepts. A spray line of length L can be viewed as a series of adjacent point sources. The total concentration produced at a point at time t is then given by summing the contributions of the individual point sources. That is,

$$\chi_L = \int_0^L \chi_p\,(L',t)\,dL' \qquad \text{(A-15)}$$

where χ_p is the concentration for a point source. Similarly, the total dosage (time-integrated concentration) is given by

$$DOS_L = \int_0^\infty dt \int_0^L \chi_p\,(L',t)\,dL' \qquad \text{(A-16)}$$

FSCBG2/FSCBG3 use complex, but analytic solutions to Equations (A-15) and (A-16).

Neglecting the restriction on vertical mixing at the top of the surface mixing layer and considering only one drop size, the peak concentration produced by a point source at downwind distance x, crosswing distance y, and height z above the surface is

$$\chi_p = \frac{Q_o}{(2\pi)^{3/2}\,\sigma_x\,\sigma_y\,\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{H'-z}{\sigma_z}\right)^2\right] + \gamma \exp\left[-\frac{1}{2}\left(\frac{H'+z}{\sigma_z}\right)^2\right]\right\} \qquad \text{(A-17)}$$

where Q_o is the spray source strength, H' is the effective release height, γ is the surface reflection coefficient, and σ_x, σ_y, and σ_z are the standard deviations of the alongwind, crosswind, and vertical concentration distributions, respectively. Based on the modeling concepts outlined by Cramer et al. (1972), the Gaussian dispersion parameters σ_y and σ_z are directly proportional to the standard deviations of the wind azimuth and elevation angles, while σ_x is directly proportional to the vertical wind-speed shear. The dosage equation corresponding to Equation (A-16) is

$$DOS_p = \frac{Q_o}{2\pi\, u\sigma_y\,\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{H'-z}{\sigma_z}\right)^2\right] + \gamma \exp\left[-\frac{1}{2}\left(\frac{H'+z}{\sigma_z}\right)^2\right]\right\} \qquad \text{(A-18)}$$

The settling and deposition of spray drops are quantified in the dispersion/deposition module by the effective release height H' and the surface reflection coefficient γ. Based on the titled plume hypothesis, H' at downwind distance x is given by

$$H' = H - vx/u \qquad \text{(A-19)}$$

where H is the actual release height. The surface reflection coefficient is the fraction of spray brought to the surface (canopy or ground in the absence of a canopy) by the combined processes of gravitational settling and atmospheric turbulence. It ranges from unity for complete reflection to zero for complete deposition. Dumbauld et al. (1976) give a semi-empirical relationship between γ and v. In the case of very large drops, the dispersion/deposition module also reduces σ_y and σ_z to account for the differences in atmospheric turbulence effects on the trajectories of small and large drops.

The deposition portion of the dispersion/deposition module is based on the fact that the fraction of the spray drops deposited between the release point and downwind distance x is given by

$$\delta = \frac{1}{\sqrt{2\pi}\,\sigma_z} \int_{-\infty}^{0} \left\{ \exp\left[-\frac{1}{2}\left(\frac{H'-z'}{\sigma_z}\right)^2 \right] + \gamma \exp\left[-\frac{1}{2}\left(\frac{H'+z'}{\sigma_z}\right)^2 \right] \right\} dz' \qquad \text{(A-20)}$$

The mass of drops remaining airborne at downwind distance x is then given by

$$Q(x) = Q_o\,(1 - \delta) \qquad \text{(A-21)}$$

The crosswind-integrated spray deposition at downwind distance x is

$$DEP_{cwi} = -\frac{dQ(x)}{dx} = \frac{d\delta}{dx} \qquad \text{(A-22)}$$

Modification of Equation (22) to account for the crosswind deposition distribution yields

$$DEP = \frac{1}{\sqrt{2\pi}\,\sigma_y}\left(\frac{d\delta}{dx}\right) \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2 \right] \qquad \text{(A-23)}$$

The dispersion/deposition module divides the spray cloud into discrete drop-size categories and sums their contributions to obtain total deposition, concentration, or dosage estimates. These calculations are greatly complicated by evaporation, which changes the drop-size distribution with time. The module assumes that drops below the canopy top follow ballistic trajectories unaffected by atmospheric turbulence until they impact a tree element or the ground.

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APPENDIX B.

COMPARISON OF CALCULATED DEPOSITION PROFILES WITH MEASUREMENTS

The FSCBG2 and FSCBG3 model deposition predictions are compared with measurements for the UN spray trials and the Program WIND forest spray trials in Figures B.1 through B.10 and B.11 through B.30, respectively. Two figures are shown for each trial of each data set. The first figure compares the deposition measurements with the deposition profiles calculated by FSCBG2/FSCBG3 with no wake effects (Model 1) and simple wake effects (Model 2). The second figure compares the deposition measurements with the deposition profiles calculated with complex wake effects by FSCBG2 and FSCBG3 (Models 3 and 4, respectively). As noted in Section 1, FSCBG2 is the mainframe version of the model and FSCBG3 is the PC version.

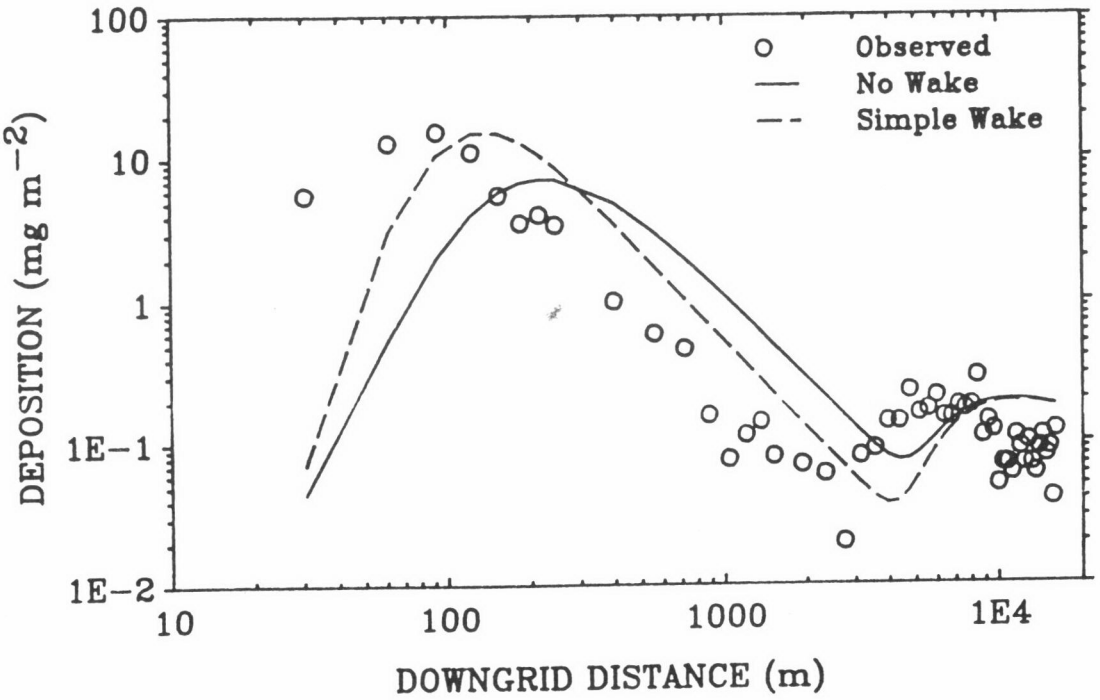

Figure B.1. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for UN Spray Trial 1-5.

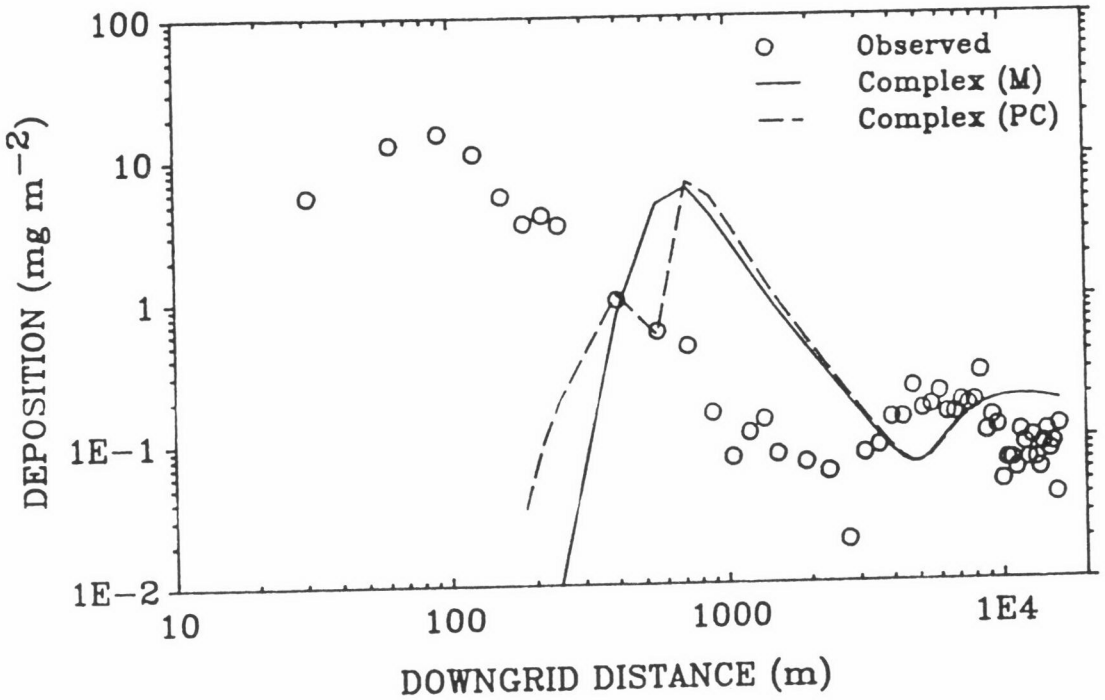

Figure B.2. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for UN Spray Trial 1-5.

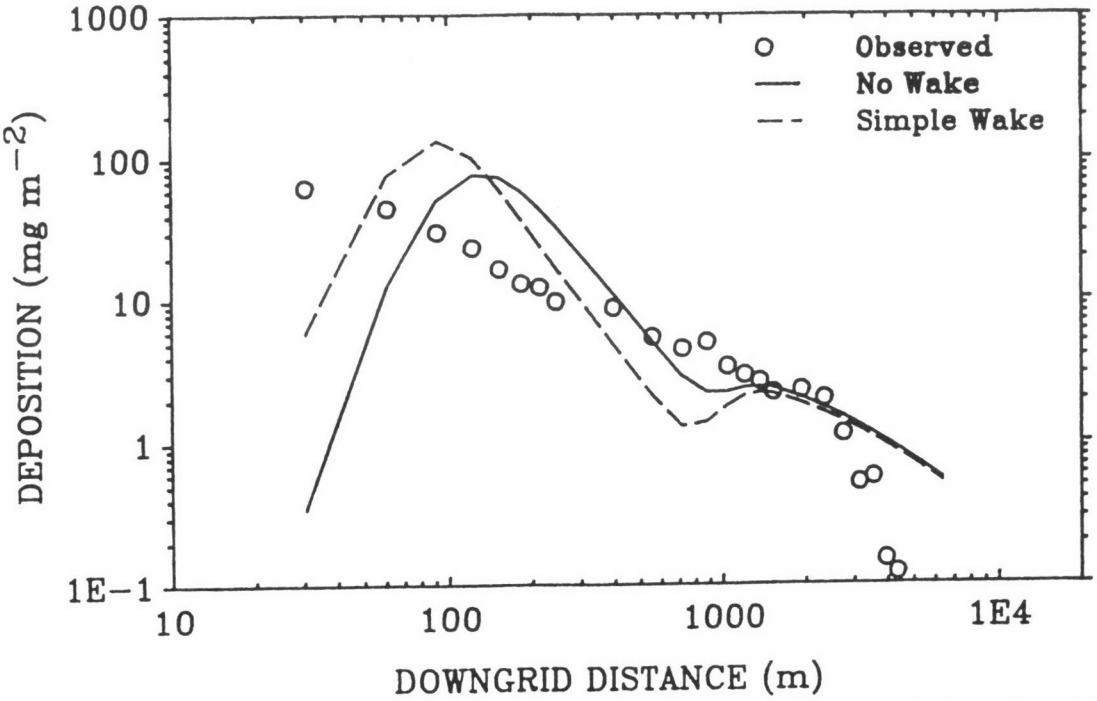

Figure B.3. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for UN Spray Trial 1-6.

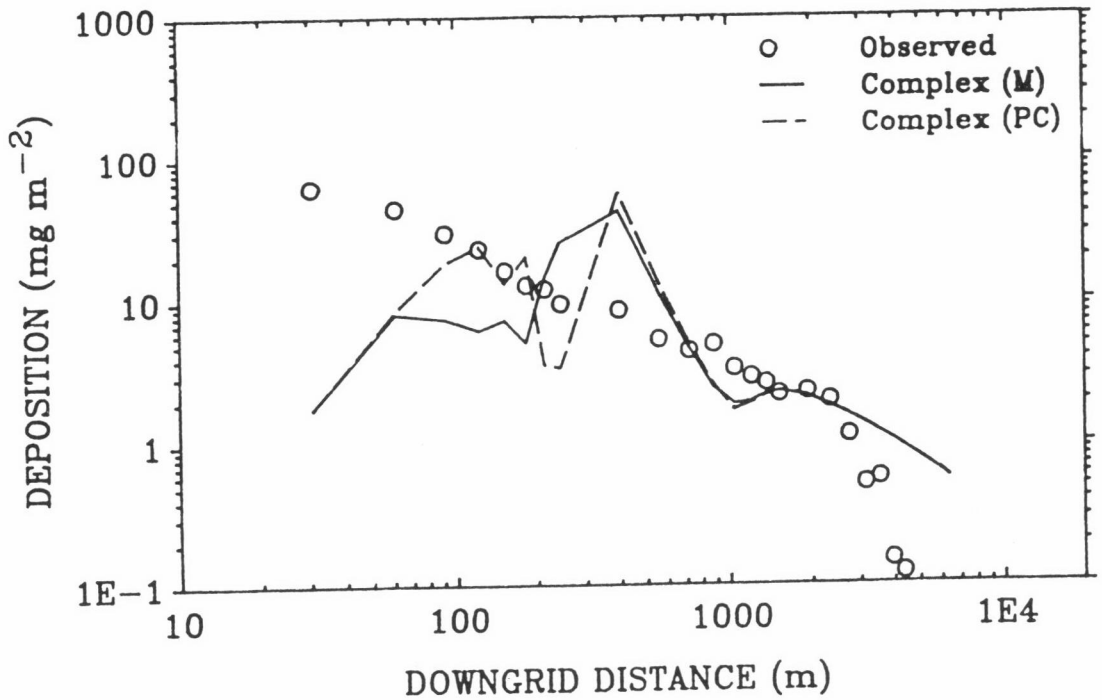

Figure B.4. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for UN Spray Trial 1-6.

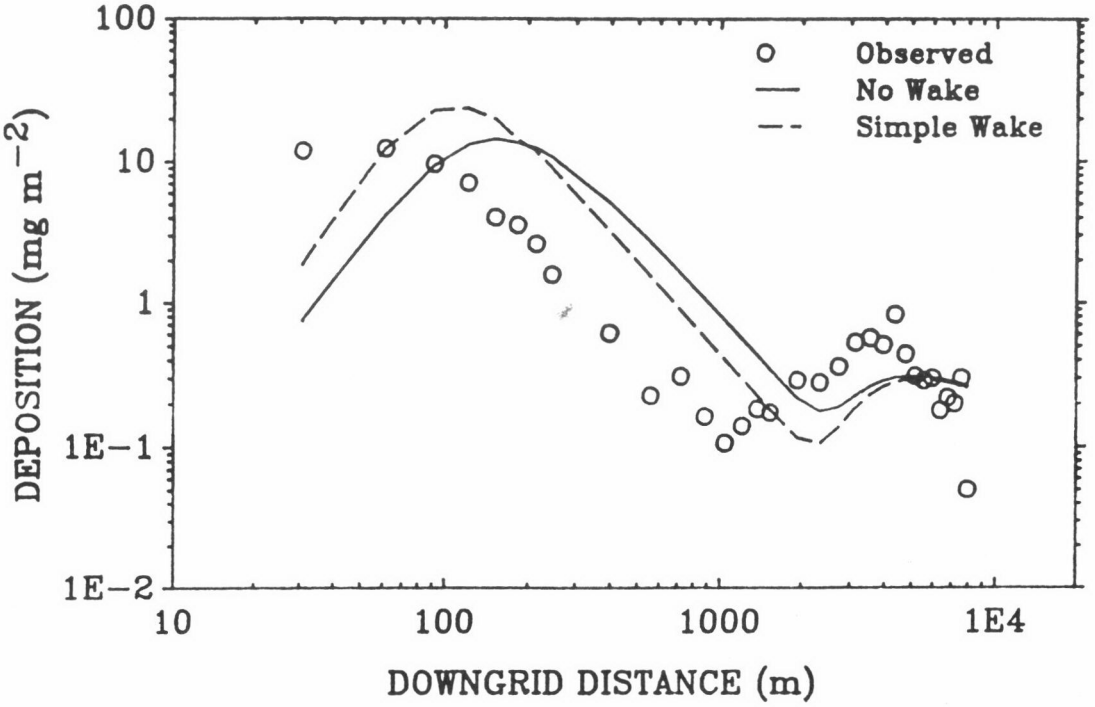

Figure B.5. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for UN Spray Trial 1-7.

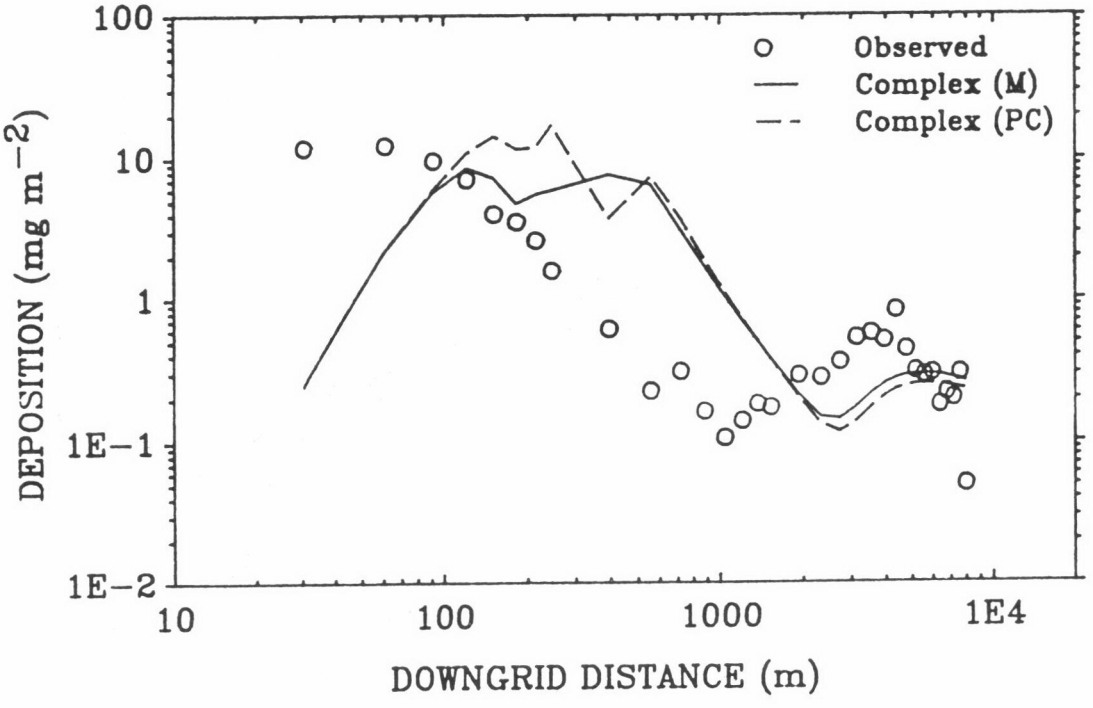

Figure B.6. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for UN Spray Trial 1-7.

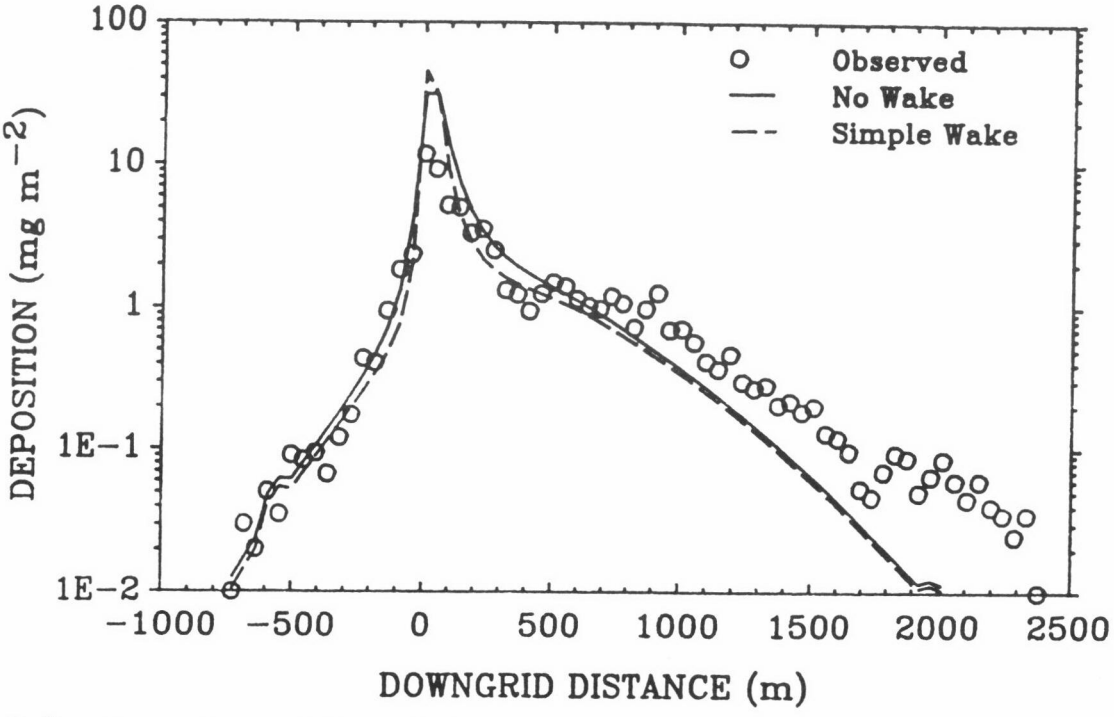

Figure B.7. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for UN Spray Trial 2-2R.

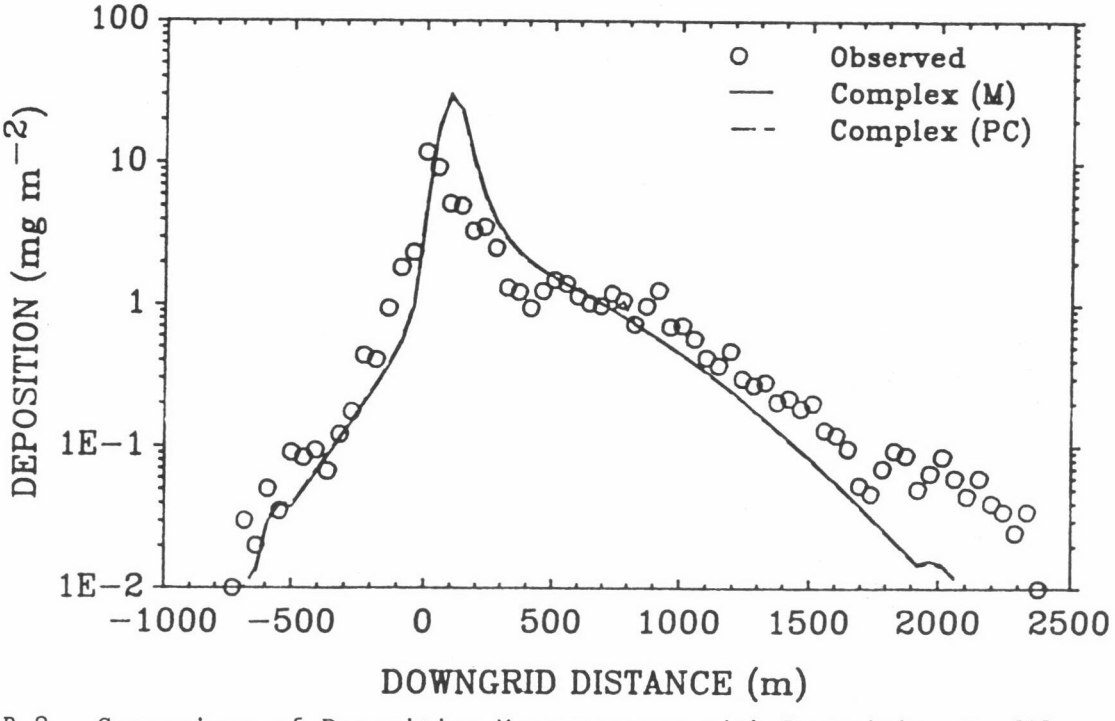

Figure B.8. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for UN Spray Trial 2-2R.

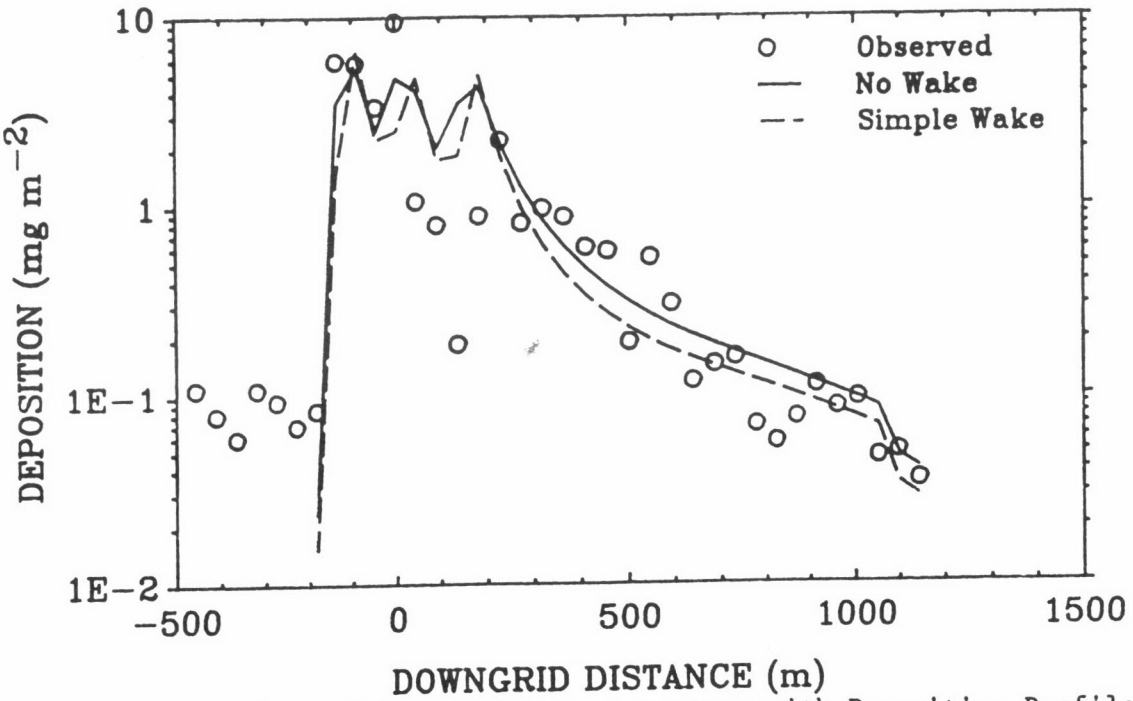

Figure B.9. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for UN Spray Trial 2-3.

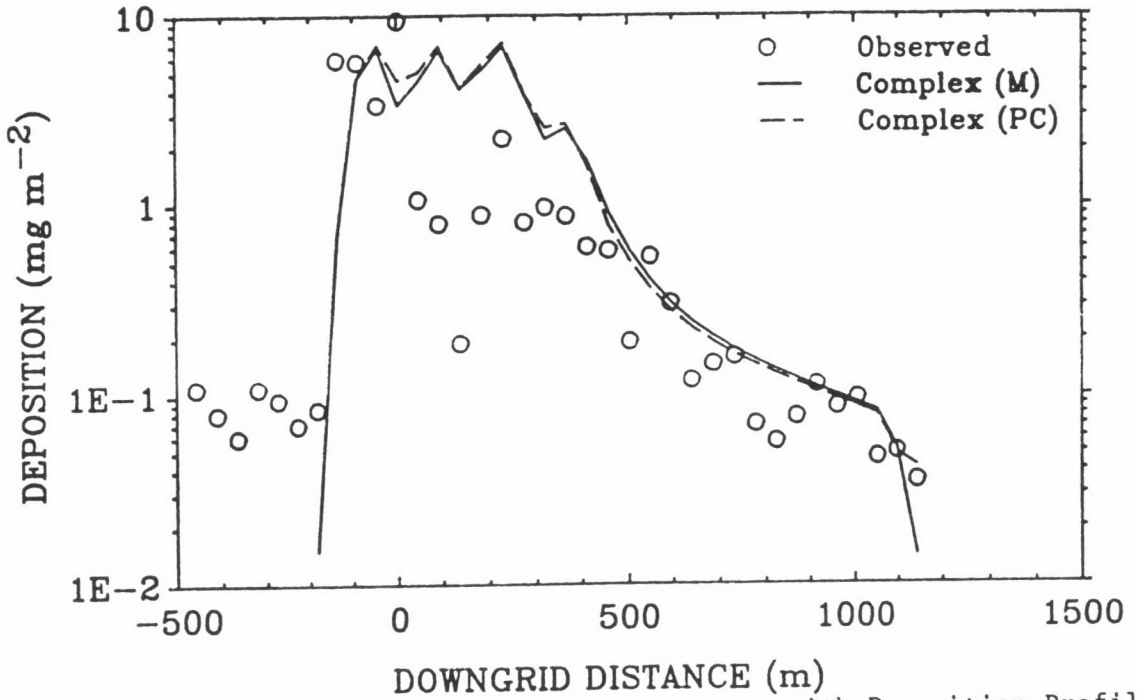

Figure B.10. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial 2-3.

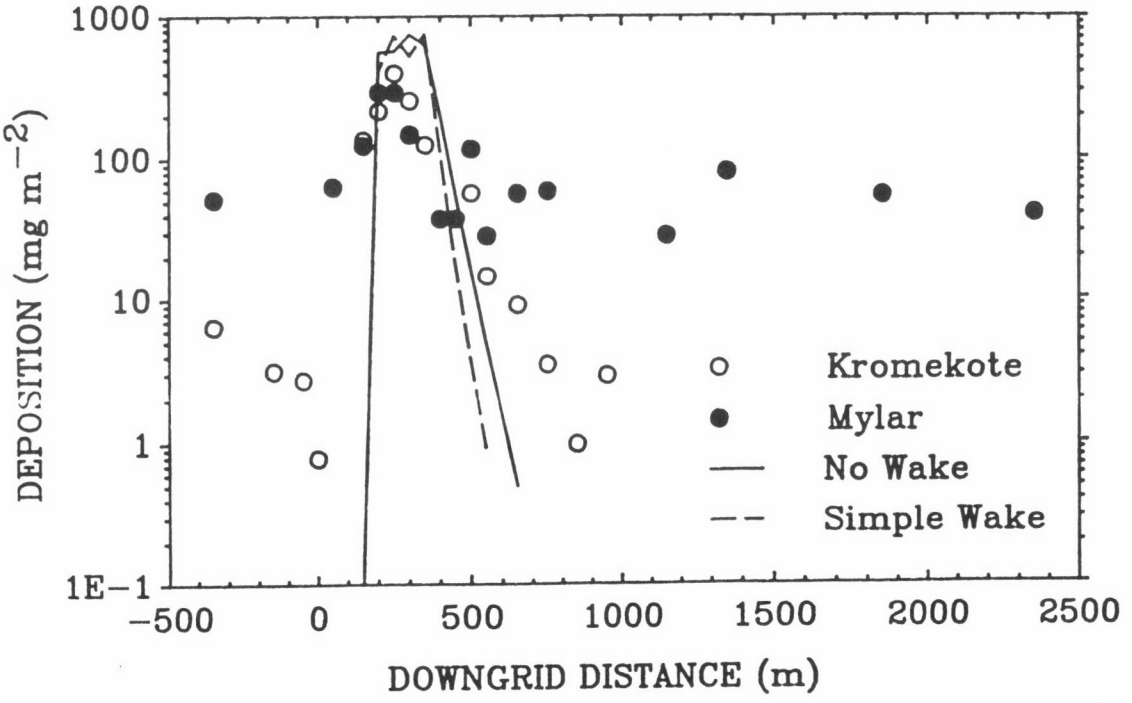

Figure B.11. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial A-1.

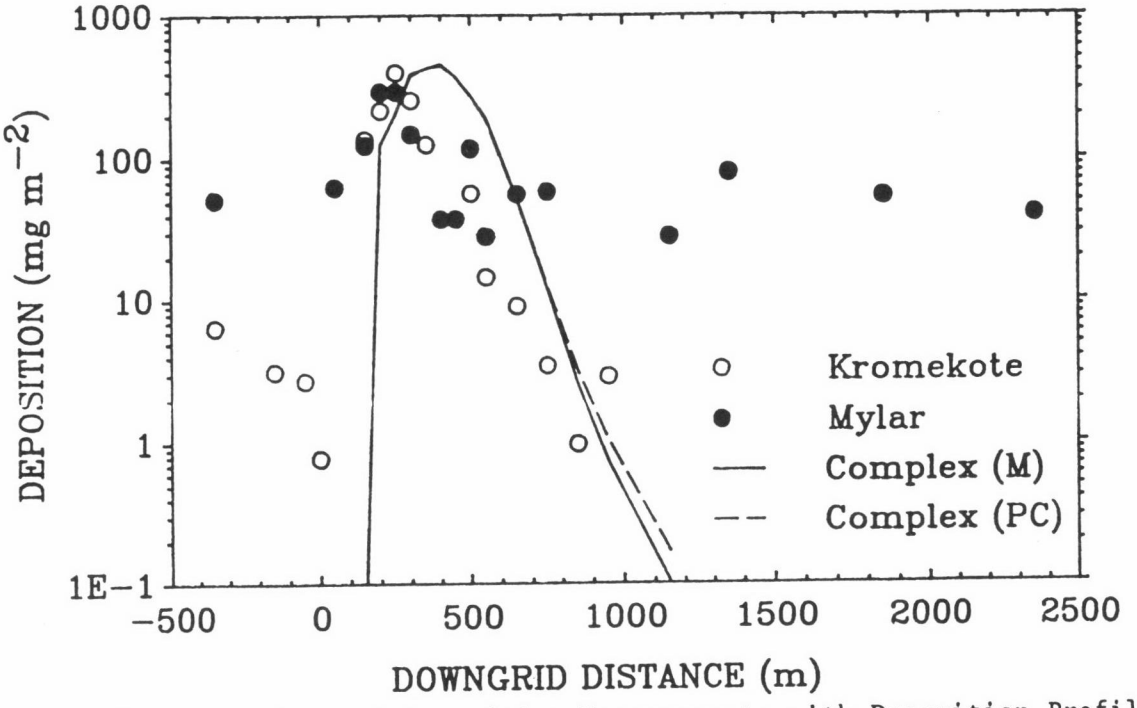

Figure B.12. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial A-1.

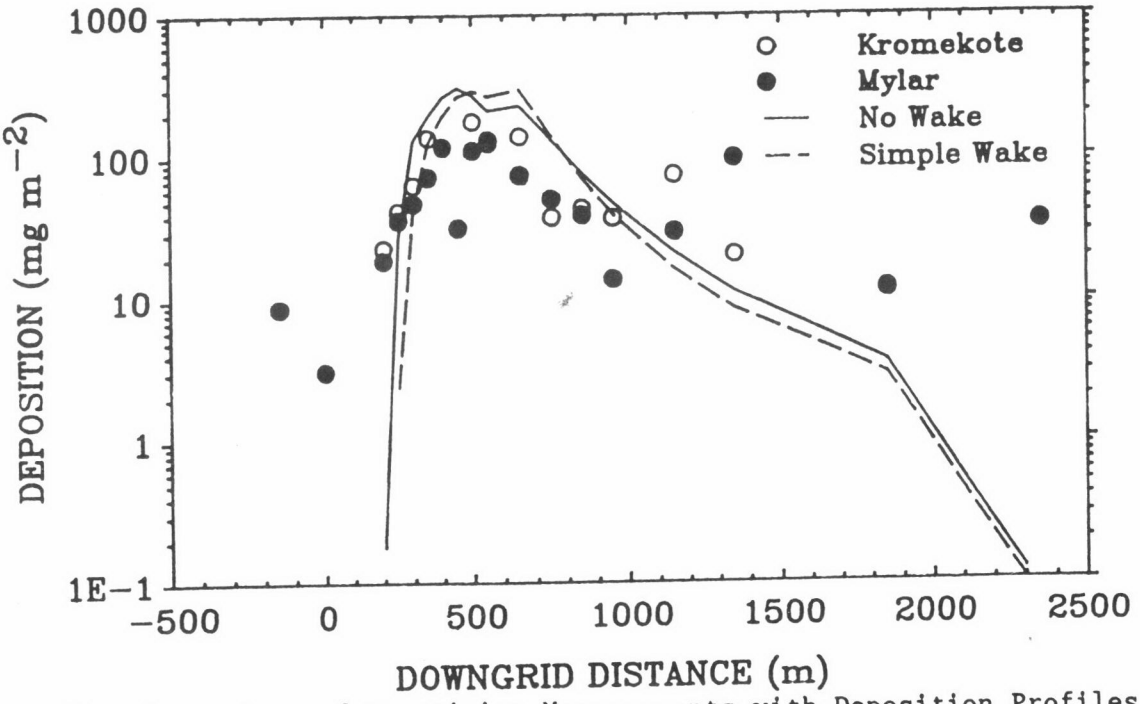

Figure B.13. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial A-2.

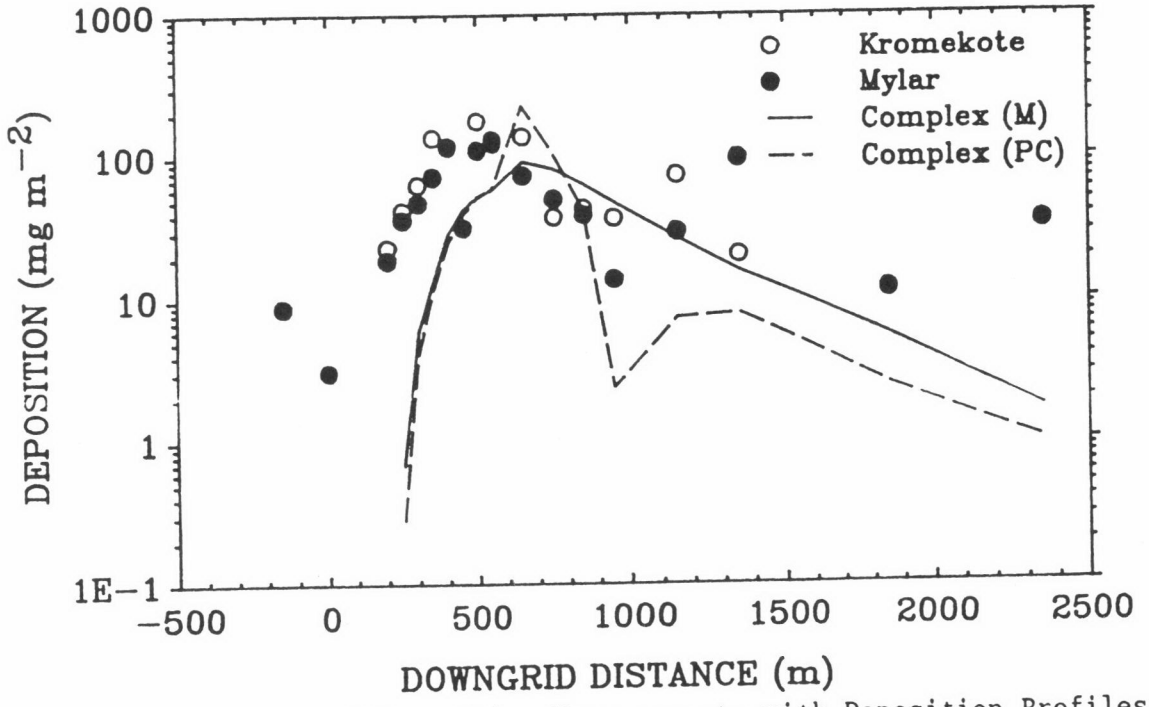

Figure B.14. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial A-2.

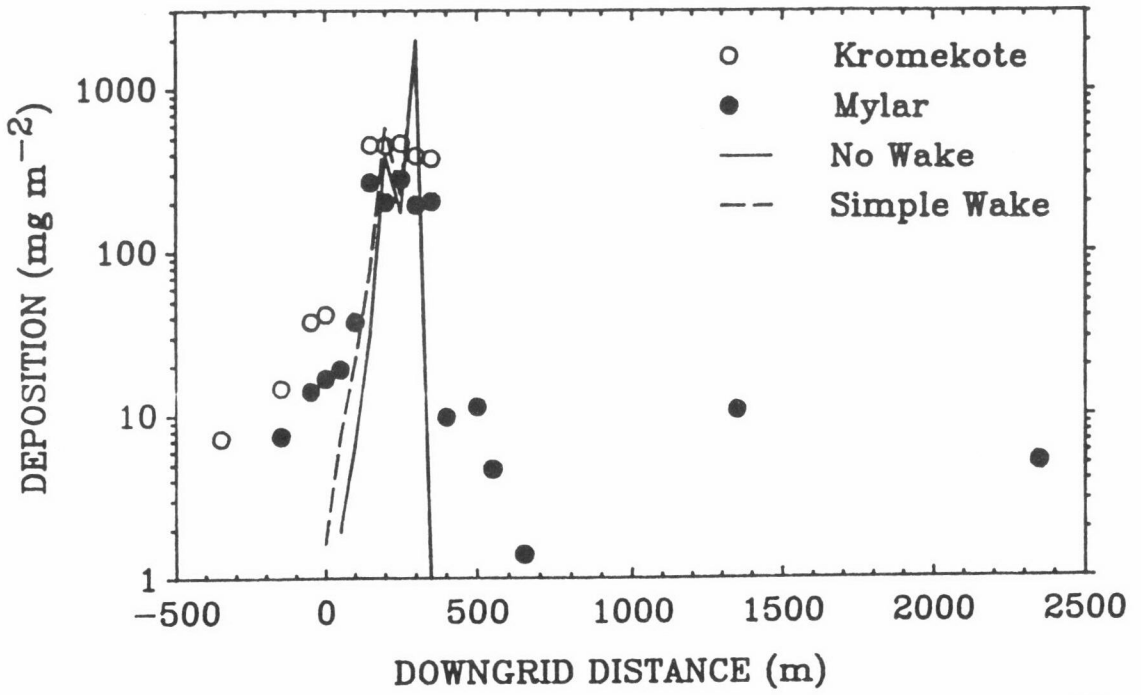

Figure B.15. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial A-3.

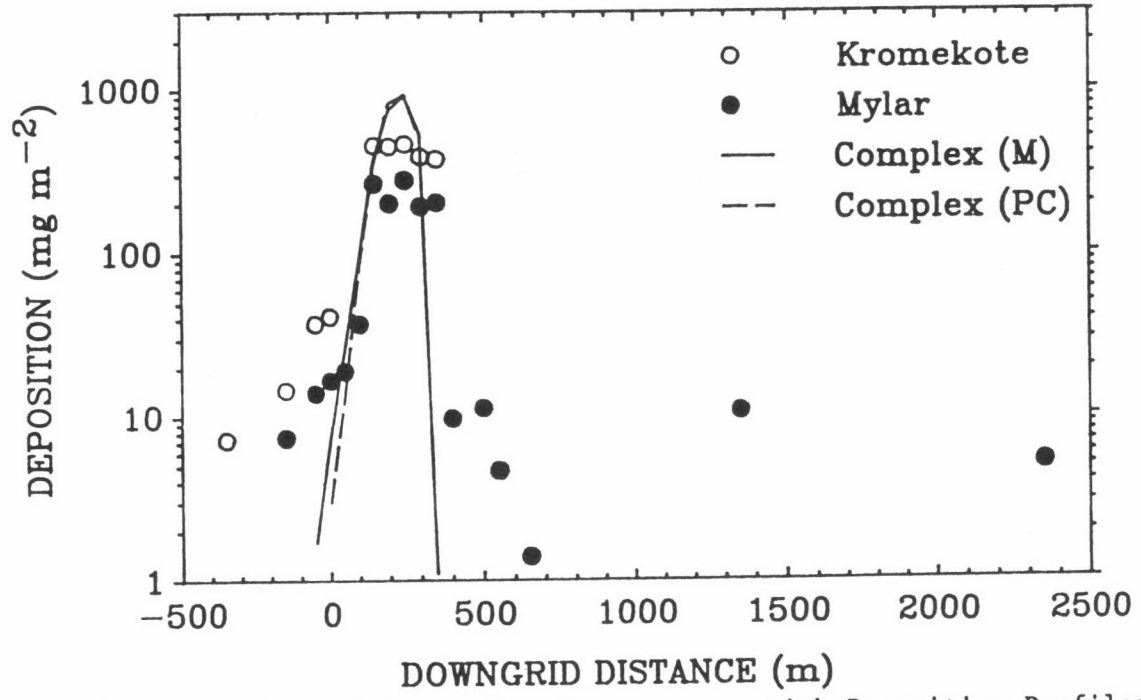

Figure B.16. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial A-3.

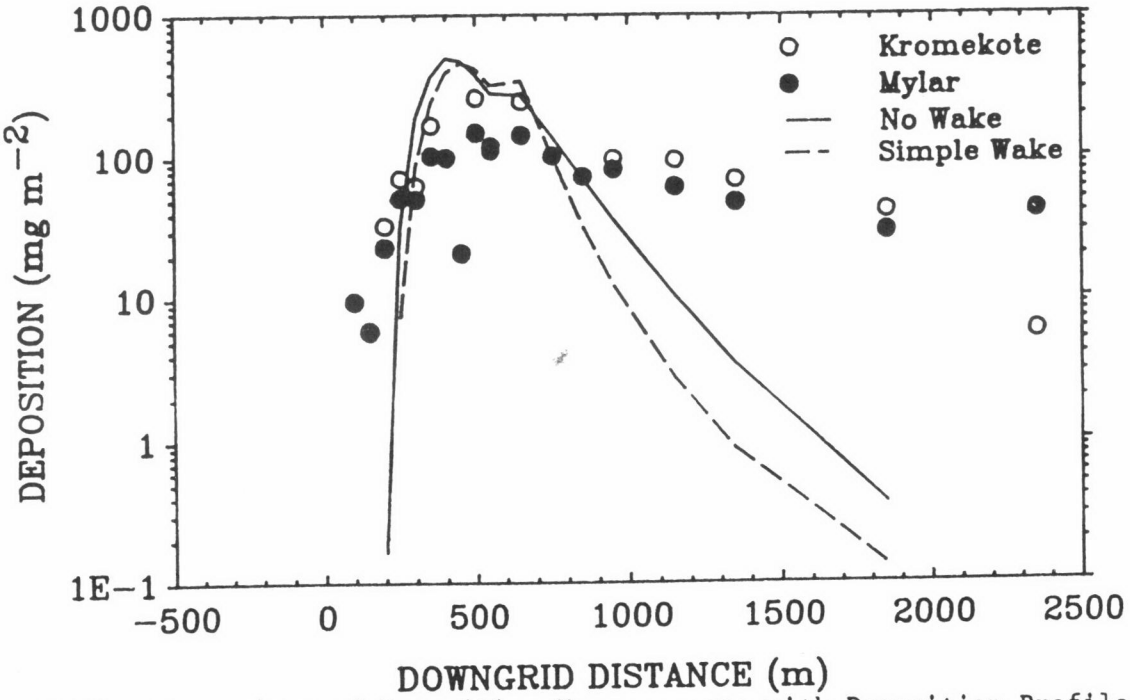

Figure B.17. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial A-4.

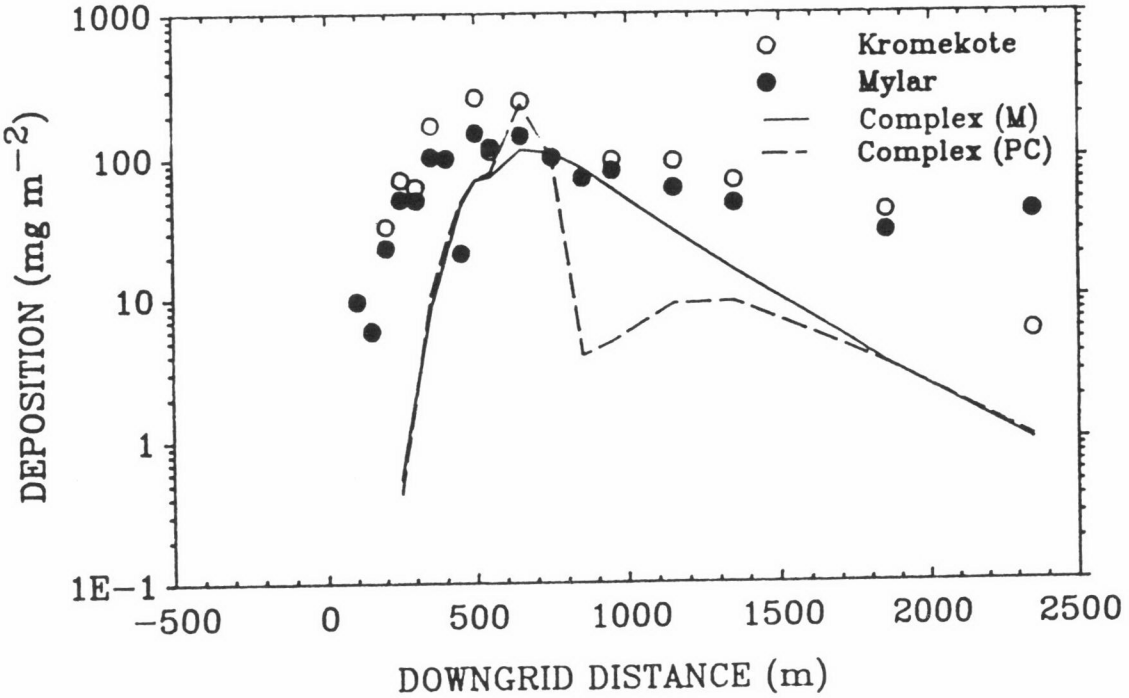

Figure B.18. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial A-4.

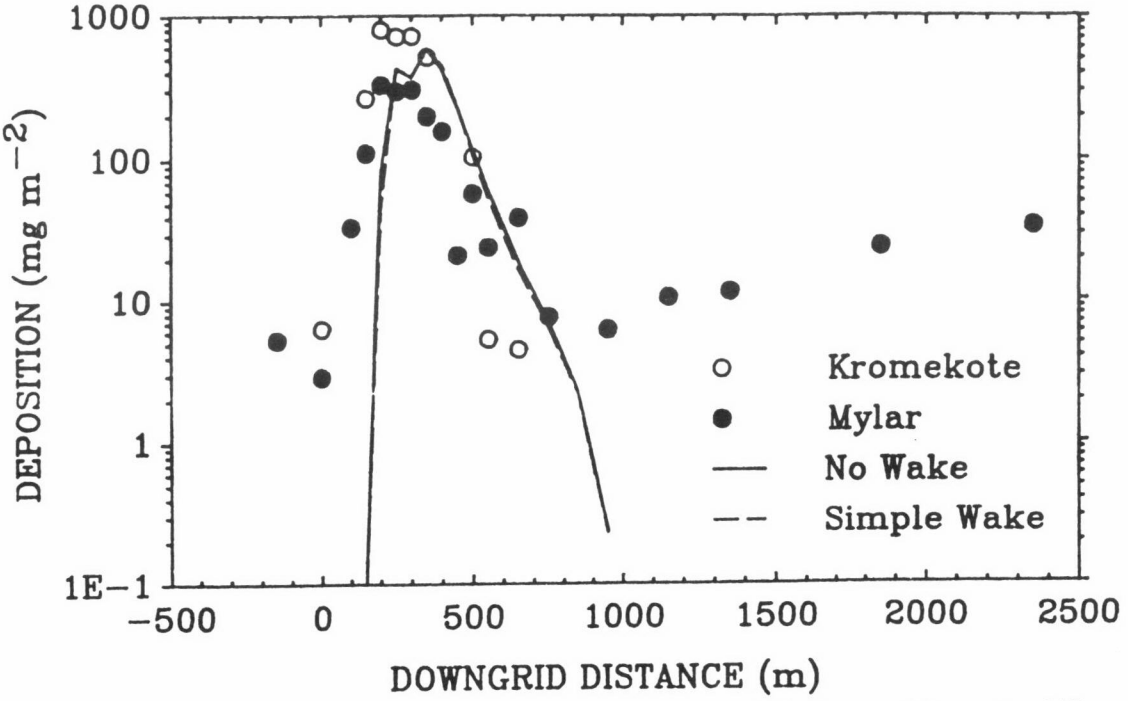

Figure B.19. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial A-5.

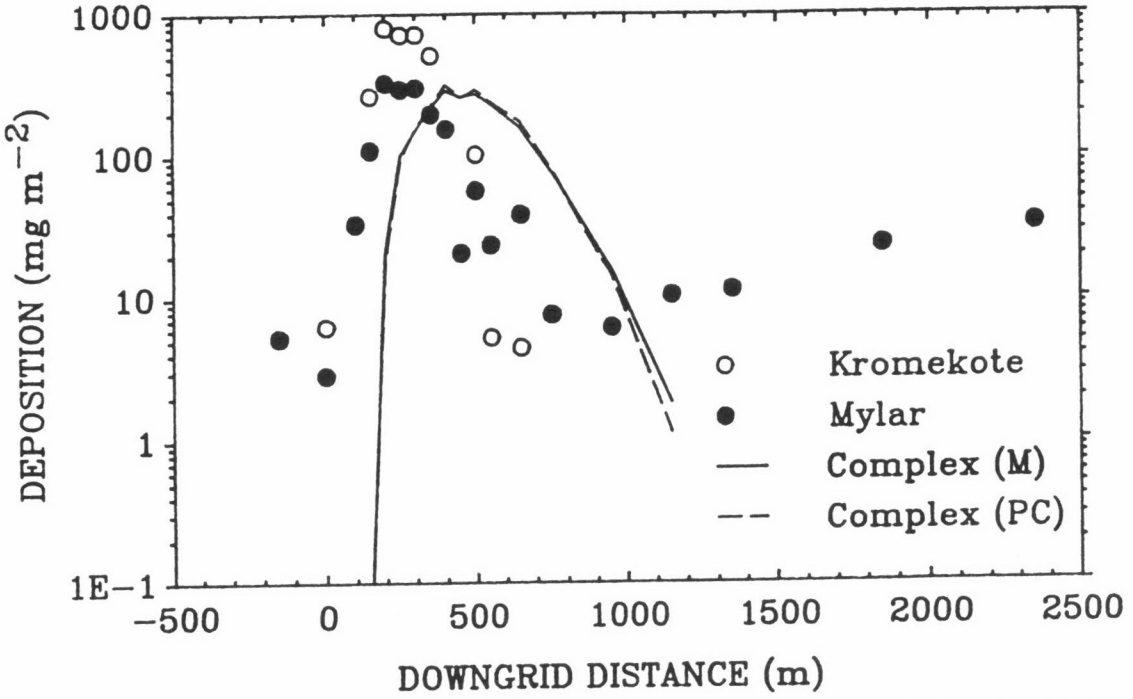

Figure B.20. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial A-5.

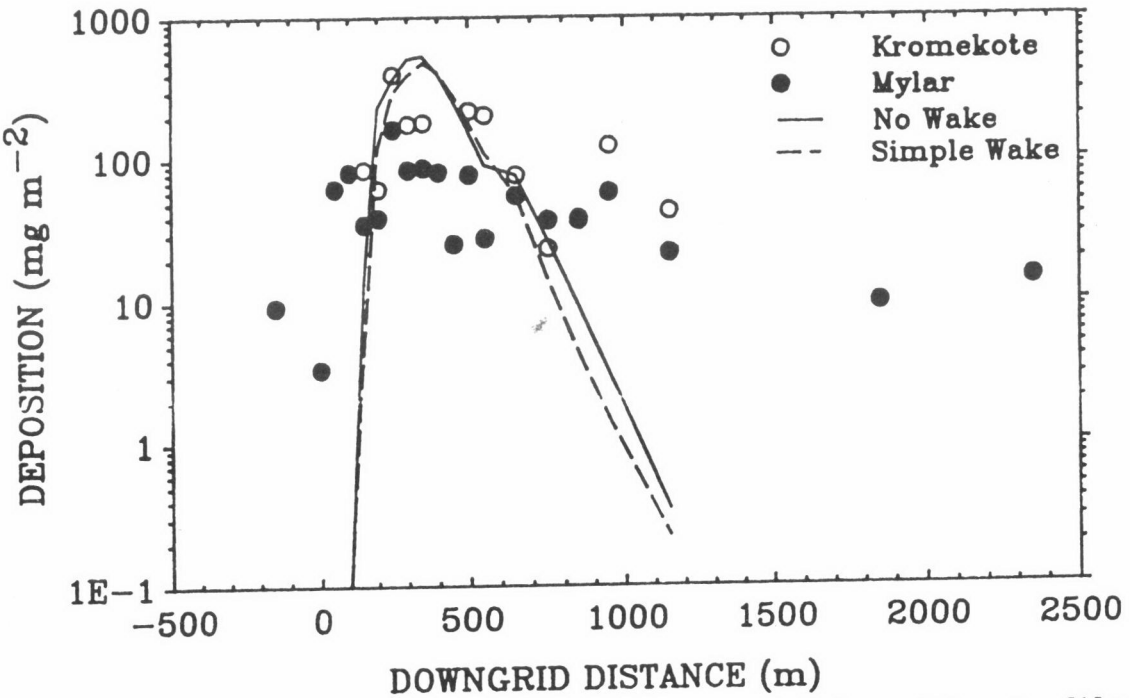

Figure B.21. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial A-6.

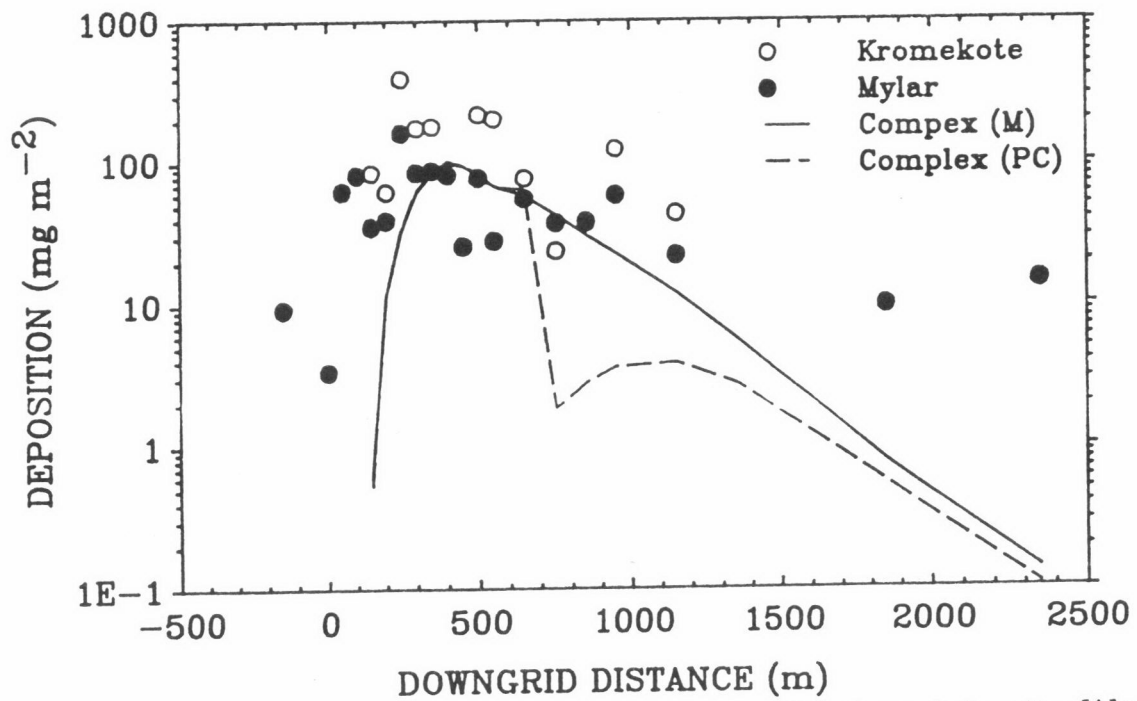

Figure B.22. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial A-6.

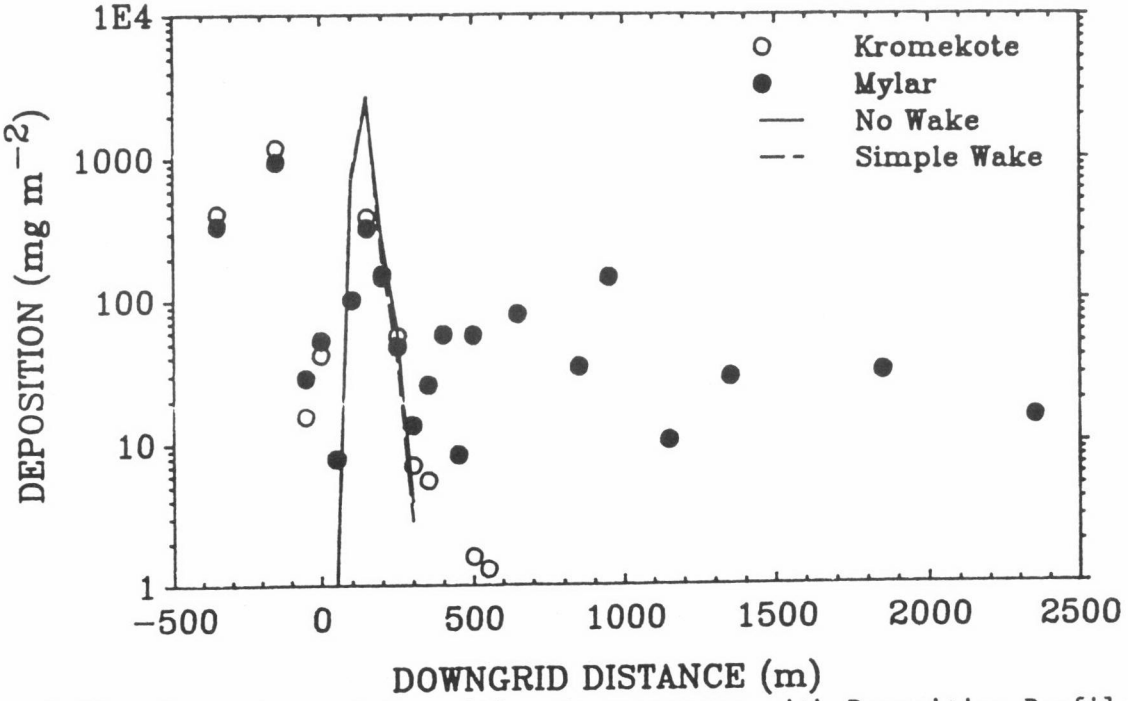

Figure B.23. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial B-1.

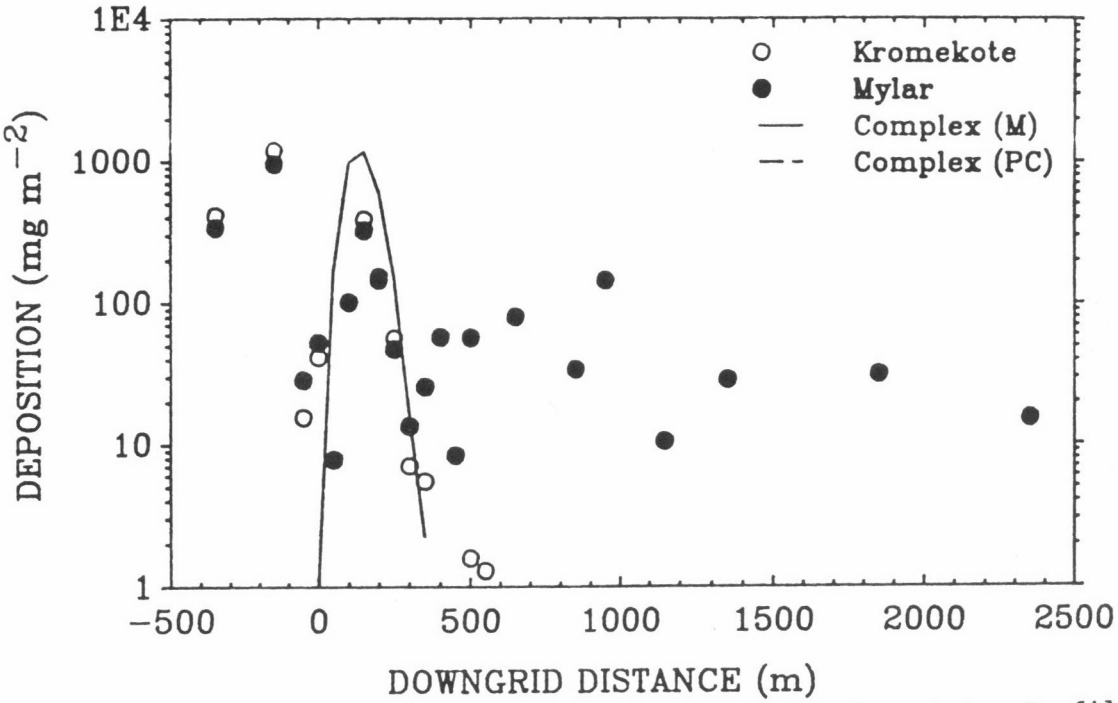

Figure B.24. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial B-1.

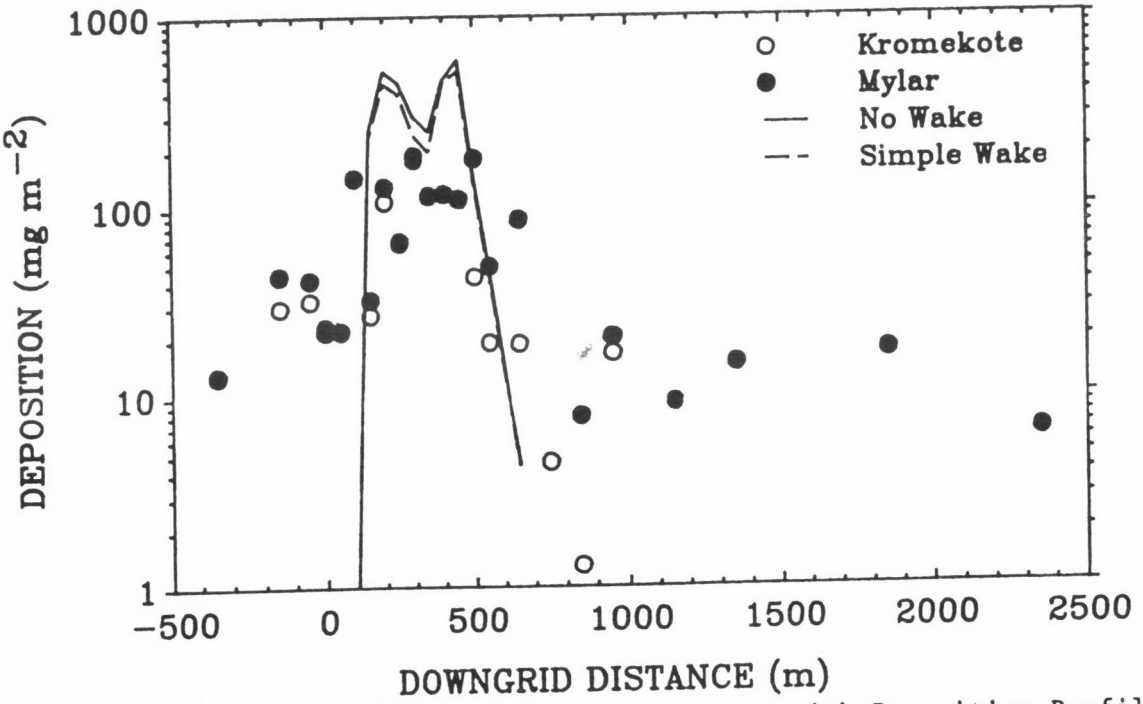

Figure B.25. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial B-2.

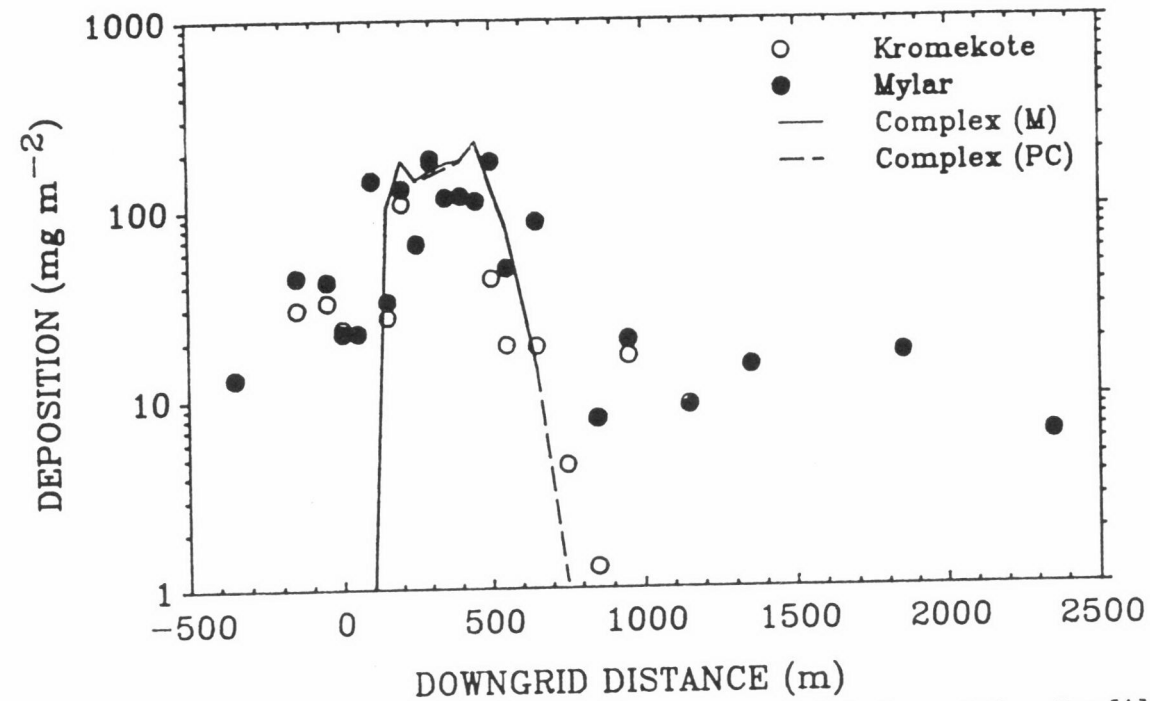

Figure B.26. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial B-2.

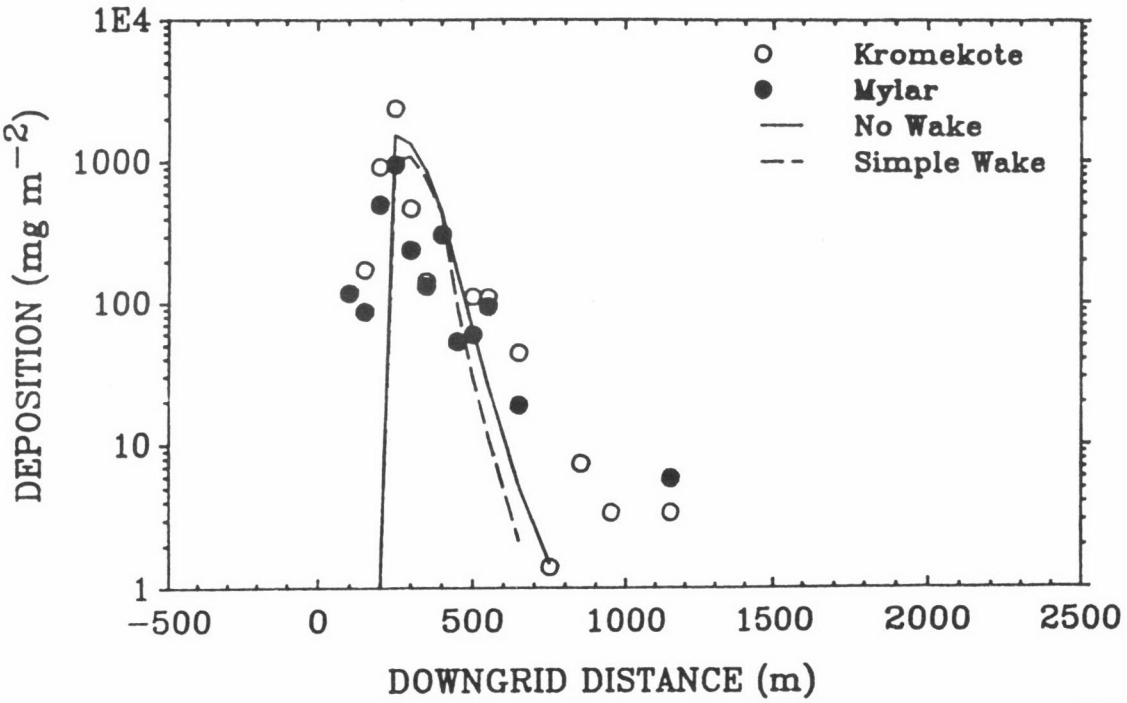

Figure B.27. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial B-3.

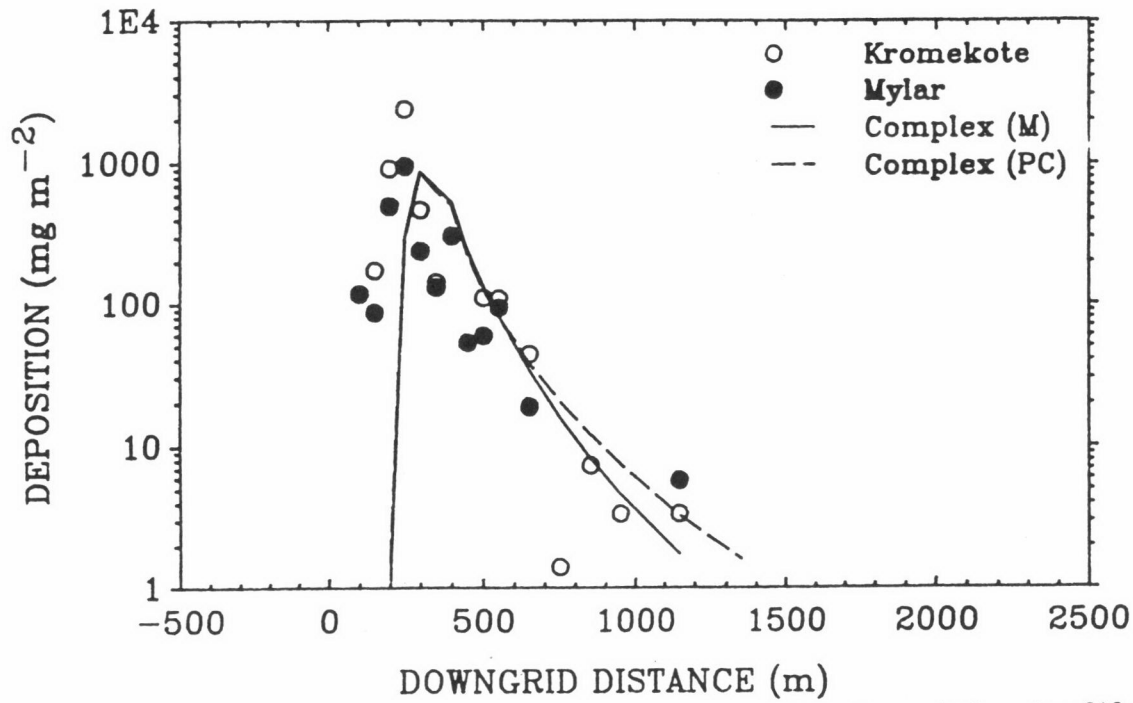

Figure B.28. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial B-3.

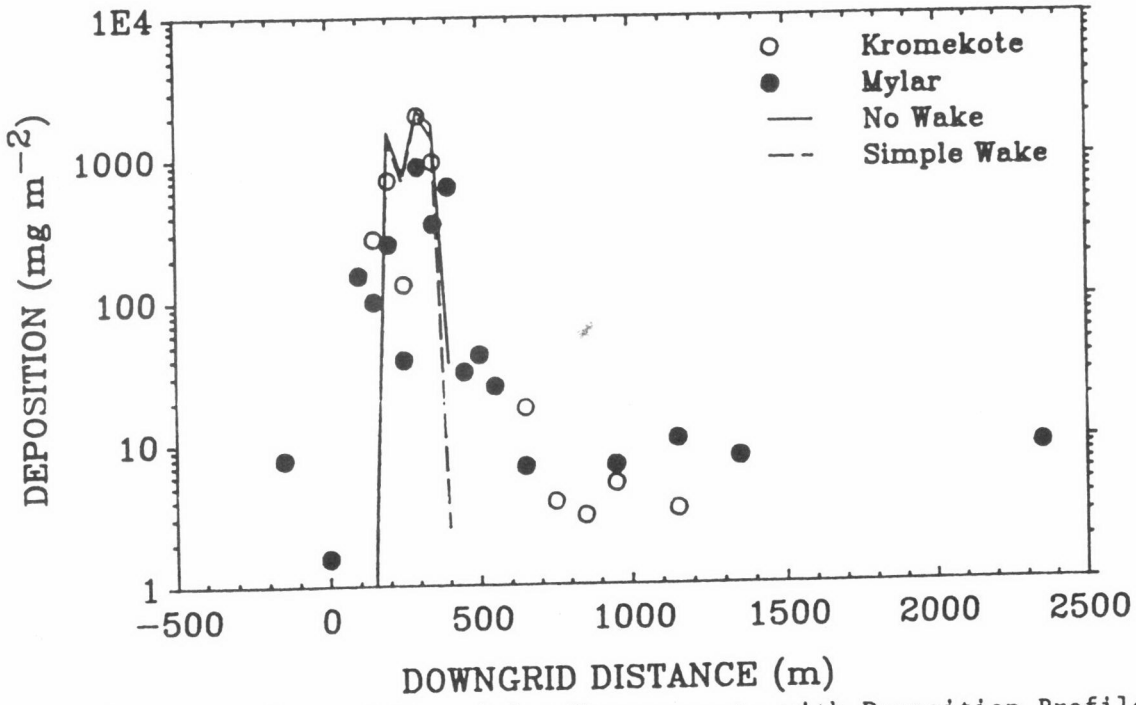

Figure B.29. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2/FSCBG3 with No Wake Effects (Model 1) and Simple Wake Effects (Model 2) for Program WIND Forest Spray Trial B-4.

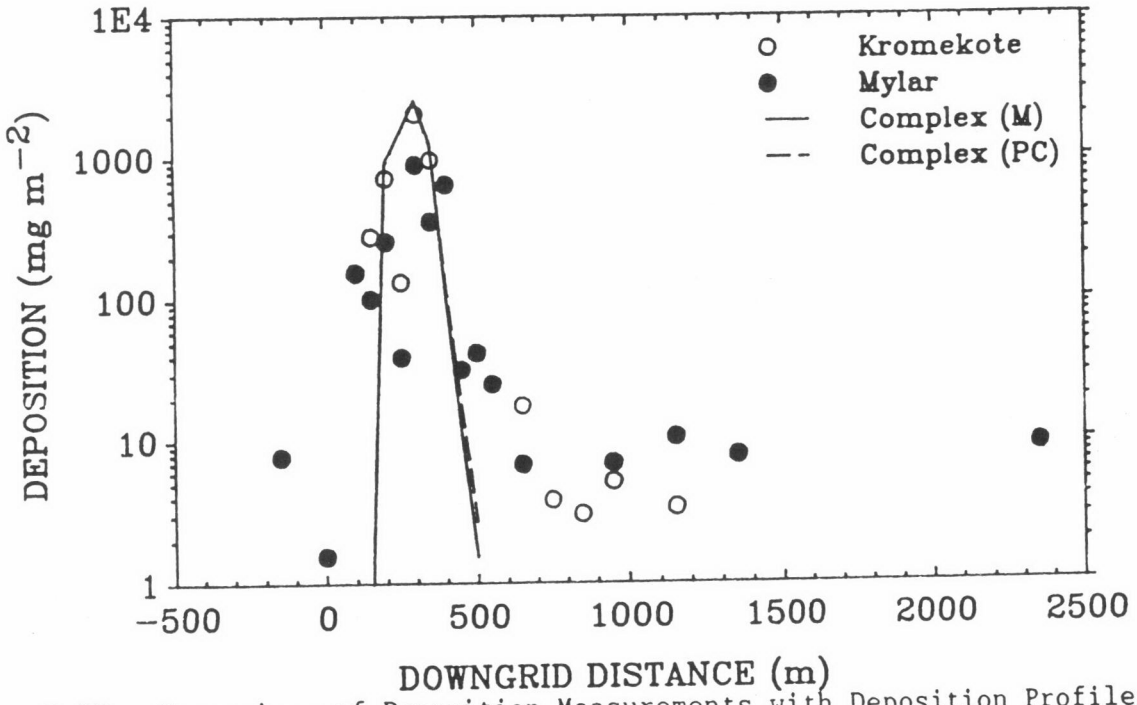

Figure B.30. Comparison of Deposition Measurements with Deposition Profiles Calculated by FSCBG2 (Mainframe) and FSCBG3 (PC) with Complex Wake Effects (Models 3 and 4, Respectively) for Program WIND Forest Spray Trial B-4.

APPENDIX C. REFERENCES

Barry, J. W. and R. B. Ekblad, 1983: Forest Service spray drift modeling 1971-1982. American Society of Agricultural Engineers Paper No. 83-1006.

Bilanin, A. J., M. E. Teske, J. W. Barry, and R. B. Ekblad, 1989: AGDISP: The aircraft spray dispersion model, code development and experimental validation. Transactions of the ASAE, 32(1), 327-334.

Bjorklund, J. R., C. R. Bowman and G. C. Dodd, 1988: User manual for the FSCBG aircraft spray and dispersion model, version 2.0. Document No. DPG/TA-88/015, U.S. Army Dugway Proving Ground, Dugway, UT. (Also available as Report No. FPM 88-5, USDA Forest Service, Davis, CA.)

Boyle, D. G., J. W. Barry, C. O. Eckard, W. T. Taylor, W. C. McIntyre, R. K. Dumbauld, and H. E. Cramer, 1975: DC-7B aircraft spray system for large-area insect control. Document No. DPG-DRC980A, U.S. Army Dugway Proving Ground, Dugway, UT.

Cramer, H. E., J. R. Bjorklund, R. K. Dumbauld, J. E. Faulkner, F. A. Record, R. N. Swanson, and A. G. Tingle, 1972: Dosage models and concepts. Document No. DTC-TR-72-609-I, U.S. Army Dugway Proving Ground, Dugway, UT.

Curbishley, T. B. and P. J. Skyler, 1989: User manual-Forest Service aerial spray computer model FSCBG(PC). FPM 89-1, USDA Forest Service, Forest Pest Management, Davis, CA.

Dumbauld, R. K., J. E. Rafferty, and H. E. Cramer, 1976: Dispersion-deposition from aerial spray releases. In Preprint Volume for Third Symposium on Atmospheric Turbulence, Diffusion, and Air Quality, American Meteorological Society, Boston, MA, 520-527.

Dumbauld, R. K., J. R. Bjorklund, and S. F. Saterlie, 1980: Computer models for predicting aircraft spray dispersion and deposition above and within forest canopies: User's manual for the FSCBG computer program. Report No. 80-11, USDA Forest Service, Methods Application Group, Davis, CA.

Dumbauld, R. K. and J. F. Bowers, 1983: Functional methodologies for characterizing wind-speed and turbulence profiles and turbulent diffusion coefficients within and above vegetative canopies and urban domain. H. E. Cramer Company, Inc. Report No. TR-83-341-01 prepared for U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM.

Fox, D. G., 1981: Uncertainty in air quality modeling. Bulletin American Meteorological Society, 62, 599-602.

Fuchs, N. A., 1959: Evaporation and Droplet Growth in Gaseous Media. Pergamon Press, New York.

Grim, B. S. and J. W. Barry, 1975: A canopy penetration model for aerially disseminated insecticide spray released above coniferous forests. Final Report under MEDC Project No. 2425, USDA Forest Service Equipment Development Center, Missoula, MT.

Hanna, S. R. 1989: Confidence limits for air quality model evaluations, as estimated by bootstrap and jackknife resampling methods. Atmospheric Environment, 23(6), 1385-1398.

Jones, D. N. 1970: Introduction to jet-engine exhaust and trailing vortex washes. Report No. 226, U.S. Air Force Air Weather Service.

Klein, K. and B. Boom, 1987: Forest site characterization. Program WIND Report FPM-87-2, USDA Forest Service, Pest Management, Davis, CA.

Prandtl, L. and O. G. Tietjens, 1934: Fundamentals of Hydro- and Aeromechanics. Dover Publications, Inc., New York.

Rafferty, J. E., J. M. White, J. F. Bowers, and J. W. Barry, 1988: Comparison of Program WIND Phase III deposition measurements with FSCBG2 model predictions. Document No. DPG/TA-89-007, U.S. Army Dugway Proving Ground, Dugway, UT.

Rafferty, J. E., J. M. White, J. F. Bowers, and R. K. Dumbauld, 1989: Forest spray dispersion study: Comparison of measured deposition with FSCBG2 model predictions. In Preprint Volume for 19th Conference Agricultural and Forest Meteorology and Ninth Conference Biometeorology and Aerobiology, American Meteorological Society, Boston, MA, 200-203.

Teske, M. E., 1986: Users manual for the computer code AGDISP Mod 4.0. USDA Forest Service, Equipment Development Center, Missoula, MT.

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